TITANIUM SHEET ROLLING PROGRAM

FOR

Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr

ELEVENTH BIMONTHLY REPORT

Covers period 1 March - 30 April 1961

Prepared Under Navy, Bureau Of Naval Weapons' Contract NOas-59-6227-c

31 August 1961

Titanium Metals Corporation of America

TECHNICAL LABORATORY

TORONTO, OHIO

TITANIUM SHEET ROLLING PROGRAM FOR
Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr

ELEVENTH BIMONTHLY REPORT

Covers Period 1 Mar - 30 Apr 1961

Prepared Under Navy, Bureau of Naval Weapons'
Contract NOas 59-6227-c

Prepared by:

D L Day, D R Mitchell, and H D Kessler

TITANIUM METALS CORPORATION OF AMERICA
TECHNICAL LABORATORY
Toronto, Ohio

TABLE OF CONTENTS

- - -

LIST OF TABLES

LIST OF TABLES - cont'd

- - -

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS - continued

LIST OF ILLUSTRATIONS - concluded

ABSTRACT

In this report period, laboratory evaluation of duplex annealed Ti-8Al-1Mo-1V sheet was completed which showed that 1850F (5 min) AC + 1100F (8 hrs) provided an optimum combination of room-and elevated-temperature tensile, subzero temperature notch tensile, and creep properties. Contamination as a result of this duplex annealing cycle was found to extend to a depth of 0.002-0.0025in, which is entirely commensurate with finish grinding and/or pickling procedures being used. A thorough evaluation of elevated-temperature tensile and elastic modulus properties and creep-stability of mill annealed Ti-8Al-1Mo-1V sheet was also completed to add to the properties being developed in the program. Half of the 92 sheets of Ti-8Al-1Mo-1V has been fully processed and testing is in progress, including property uniformity studies on one representative sheet. Longitudinal tensile and bend properties were measured on the balance of these sheets. The last 1700-pound ingot of Ti-8Al-1Mo-1V was pressed to slab, chemically analyzed, and processing of 32 additional sheets was scheduled.

A more extended study of the effect of finish annealing temperature on the creep-stability properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets resulted in the selection of 1650F (1/2 hr) AC as the optimum final annealing cycle for both alloys, although, in the course of this work, the need was recognized for more information on depth of process contamination and its relation to stability of Ti-7Al-12Zr. Preliminary evaluation of welded Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr was conducted, showing that good as-welded and welded-and-annealed properties can be achieved. Other laboratory investigations are in progress including hydrogen studies and a more thorough evaluation of various elevated-and sub-zero temperature properties. The 26 sheets from the first two ingots were finish annealed at 1650F (1/2 hr) AC, ground, pickled, and are being tested, including property uniformity studies on one 0.062in sheet of each alloy. In the production phase of the contract,

six 1700-pound ingots were pressed to slabs, chemically analyzed, and processing was initiated on 74 sheets of Ti-5Al-5Sn-5Zr and 69 sheets of Ti-7Al-12Zr. However, because of some unexpected material losses, another 1700-pound ingot of each alloy is being melted with processing to be initiated in the next report period.

— — —

ELEVENTH BIMONTHLY REPORT

TITANIUM SHEET ROLLING PROGRAM FOR Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr

INTRODUCTION

The purpose of Contract NOas 59-6227-c is to establish optimum sheet processing procedures for three advanced alpha or essentially all-alpha titanium alloys; Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr; and to produce substantial quantities of sheet from each of the three for evaluation by Department of Defense contractors.

During previous report periods one 3500-pound ingot of Ti-8Al-1Mo-1V was processed to sheet and optimum finish rolling and mill annealing temperatures were established. In the production phase of the contract, five 1600-pound ingots of Ti-8Al-1Mo-1V were finish rolled and mill annealed, and melting of a sixth ingot was initiated. Initial sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr were rolled from two 1700-pound ingots and evaluated to establish the optimum finish rolling temperature. Additional studies were required to determine the optimum finish annealing cycle. The balance of material from the two heats was processed to sheet, mill annealed, and test panels cut for evaluation prior to final annealing. Three 1700-pound ingots of each of the two alloys was melted and scheduled for sheet processing in the production phase of the contract.

In this, the eleventh report period covering 1 March - 30 April 1961, additional property evaluation was completed on Ti-8Al-1Mo-1V including elastic modulus, standard elevated-temperature tensile, sub-zero temperature notch tensile, and creep-stability properties in both the mill annealed and duplex annealed conditions. Finishing operations were substantially completed on half of the Ti-8Al-1Mo-1V sheets and testing is in progress. Processing of an additional 1700-pound ingot of Ti-8Al-1Mo-1V was initiated.

Evaluation of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr was continued and the optimum finish annealing cycle was established to permit finishing operations to be resumed on the balance of sheets from the first two heats. The three 1700-pound ingots of each alloy were pressed to slab, chemically analyzed, and several sheets were finish rolled. Melting of one additional heat of each of the two alloys was scheduled to insure that sufficient material will be available for the production phase of the contract.

EVALUATION OF Ti-8Al-1Mo-1V SHEET

As described in the Eighth Bimonthly Report(1), duplex annealing temperatures in excess of 1800F (5 min) AC + 1100F (8 hrs) provided much improved creep resistance. Therefore, a more thorough evaluation of the other properties such as bend radii, notch tensile characteristics, elastic modulus, and elevated temperature strengths was undertaken on a number of Ti-8Al-1Mo-1V sheets to determine the optimum duplex annealing cycle. Results of this evaluation are discussed in the sections to follow.

Effect of Duplex Annealing on Properties of Ti-8Al-1Mo-1V Sheet

Notch and Standard Tensile and Bend Properties

Results of standard room temperature tensile and bend tests on three early sheets of Ti-8Al-1Mo-1V are listed in Table 1 and notch and unnotched tensile data from a more comprehensive investigation of three recent sheets is presented in Table 2. Duplex annealing cycles were confined to the range of 1825F (5 min) AC + 1100F (8 hrs), since prior properties had been obtained at lower temperatures (1800F) and temperatures above 1875F were avoided because of the possibility of exceeding the beta transus (approximately 1880-1900F). All specimens were cut from Ti-8Al-1Mo-1V sheets in the indicated mill annealed condition and heat treated in the laboratory.

Room-temperature strengths generally decreased and tensile elongation increased with increasing sheet thickness, observations that have been noted previously in the mill annealed condition. Although not completely consistent, bendability decreased slightly at the heavier gages.

Regarding the effect of solution temperature in the duplex annealing cycle, slightly higher strengths were obtained at 1850 and 1875F compared to 1825, although the differences were not appreciably large. Little difference was observed in tensile elongation values, although the minimum bend radius increased at the higher solution temperatures, particularly at 1875F. Elevated temperature strengths were somewhat higher than previously achieved at 800 and 1000F on samples duplex annealed at 1800F (5 min) AC + 1100F (8 hrs)[2]. However, it should be noted that the results in Table 2 were obtained on longitudinal specimens from sheets which exhibited 10-15 Ksi higher strength (due to reverse directionality) than those used earlier[2].

Tensile test results at sub-zero temperatures in Table 2 show that tensile elongation decreased and strength increased as the temperature was lowered; however, no evidence of brittle fractures at -320F was observed. Elongation values at -320F were somewhat higher for material duplex annealed at 1825F (5 min) AC + 1100F (8 hrs). Good notch strengths were also obtained at sub-zero temperatures, although the notch-strength ratio at K_t=6.0 was somewhat lower at -320F than at room temperature or -110F. However, except for two instances, all ratios were 1.0 or greater with little difference between the two duplex annealing cycles.

Modulus of Elasticity

Prior to Contract NOas 59-6227-c, some preliminary measurements were made at Armour Research Foundation on two early heats of Ti-8Al-1Mo-1V to determine the modulus of elasticity dynamically. This procedure consists of vibrating a specimen at its natural resonant frequency and calculating the modulus of elasticity from the following equation:

TABLE I ROOM TEMPERATURE TENSILE AND BEND PROPERTIES OF SEVERAL DUPLEX ANNEALED Ti-8Al-1Mo-1V SHEETS (Averages of Duplicate Tests)

Condition	Dir	UTS, Ksi	YS(0.2%), Ksi	Elong (2"), %	MBR, T
0.020", M-9519, S-1807, Orig. Mill Annealed 1400-1450F (8 hrs) -					
1825F (5 min) AC + 1100F (8 hrs)	L	166.7	155.9	10.5	4.0
"	T	174.6	161.9	10.0	3.2
1850F (5 min) AC + 1100F (8 hrs)	L	179.6	158.9	6.5	4.0
"	T	181.5	164.2	9.5	3.0
1875F (5 min) AC + 1100F (8 hrs)	L	168.6	152.7	4.0	5.3
"	T	172.0	156.3	4.5	5.0
0.062", M-9519, A-3713 Sheet No. 3, Orig. Mill Annealed 1350F (8 hrs) -					
1825F (5 min) AC + 1100F (8 hrs)	L	155.5	144.2	13.0	2.8
"	T	157.5	144.4	14.8	2.8
1850F (5 min) AC + 1100F (8 hrs)	L	158.5	143.9	14.3	3.5
"	T	162.0	146.7	15.0	2.8
1875F (5 min) AC + 1100F (8 hrs)	L	153.6	136.1	6.5(1)	5.0
"	T	160.2	141.4	11.5	4.0
0.096", M-9519, A-3700 Sheet No. 4, Orig. Mill Annealed 1350F (8 hrs) -					
1825F (5 min) AC + 1100F (8 hrs)	L	144.1	133.1	17.0	3.5
"	T	143.3	130.3	15.3	4.0
1850F (5 min) AC + 1100F (8 hrs)	L	149.6	139.2	14.5	3.3
"	T	147.5	134.2	16.5	4.0
1875F (5 min) AC + 1100F (8 hrs)	L	148.4	129.5	13.5	4.7
"	T	151.1	132.5	11.3	5.0

(1) Broke at end of gage length.

TABLE 2 NOTCH AND STANDARD TENSILE PROPERTIES AT VARIOUS TEMPERATURES OF DUPLEX ANNEALED Ti-8Al-1Mo-1V SHEET (All sheets originally mill annealed 1450F (4 hrs); averages of duplicate tests)

Test Temp, F	Dir	UTS, Ksi	YS(0.2%), Ksi	Elong(2"), %	MBR, T	Notch Properties* K_t	Notch Properties* NTS, Ksi	Notch Properties* NSR
0.025", V-1554M, A-5491 Sheet No. 1 -								
Condition: 1825F (5 min) AC + 1100F (8 hrs)								
-320	L	245.9	-	8.0(1)	-	3.0	273.3	1.11
-320	L	-	-	-	-	6.0	247.3	1.01
-110	L	194.9	169.4	5.0(1,2)		3.0	222.8	1.14
-110	L	-	-	-	-	6.0	205.1	1.05
RT	L	172.5	158.5	11.5	2.1	3.0	193.2	1.13
RT	T	162.4	154.0	8.3	2.1	-	-	-
RT	L	171.6	158.4	14.3(1)	-	6.0	189.0	1.10
800	L	122.3	99.4	6.0	-	-	-	-
1000	L	104.3	83.9	6.0	-	-	-	-
Condition: 1850F (5 min) AC + 1100F (8 hrs)								
-320	L	246.1	241.4	7.0(1)	-	3.0	283.1	1.14
-320	L	-	-	-	-	6.0	251.3	1.02
-110	L	203.4	187.4	8.0(1)	-	3.0	221.2	1.09
-110	L	-	-	-	-	6.0	188.5	0.93
RT	L	167.2	152.5	10.0	3.2	3.0	192.9	1.12
RT	T	165.7	154.5	6.5	2.1	-	-	-
RT	L	173.0	157.2	11.3(1)	-	6.0	188.7	1.09
800	L	124.3	102.9	5.5(2)	-	-	-	-
1000	L	107.8	86.6	8.7	-	-	-	-
Condition: 1875F (5 min) AC + 1100F (8 hrs)								
RT	L	178.4	159.1	12.0	3.2			
RT	T	168.6	153.2	6.0	3.2			

(continued)

(Table 2 - continued) Sheet 2

Test Temp, F	Dir	UTS, Ksi	YS(0.2%), Ksi	Elong(2"), %	MBR, T	Notch Properties* K_t	NTS, Ksi	NSR
0.050", V-1553B, A-5472, Sheet No. 2 -								
Condition: 1825F (5 min) AC + 1100F (8 hrs)								
-320	L	242.0	227.5	9.0(1)	-	3.0	270.1	1.12
-320	L	-	-	-	-	6.0	231.5	0.96
-110	L	194.8	177.7	13.0(1)	-	3.0	216.6	1.11
-110	L	-	-	-	-	6.0	210.9	1.08
RT	L	168.6	155.4	13.0	2.5	3.0	194.0	1.13
RT	T	158.5	149.9	12.0	2.8	-	-	-
RT	L	171.7	155.9	17.3(1)	-	6.0	183.4	1.07
800	L	122.9	101.0	9.7	-	-	-	-
1000	L	106.7	86.3	15.5	-	-	-	-
Condition: 1850F (5 min) AC + 1100F (8 hrs)								
-320	L	238.4	224.0	7.0(1, 2)	-	3.0	284.8	1.19
-320	L	-	-	-	-	6.0	245.6	1.03
-110	L	174.8	174.8	2.0(1, 3)	-	3.0	216.2	(3)
-110	L	-	-	-	-	6.0	205.3	(3)
RT	L	170.0	156.7	15.0	2.8	3.0	192.6	1.11
RT	T	159.2	148.2	12.0	2.8	-	-	-
RT	L	173.9	158.0	15.8(1)	-	6.0	184.9	1.06
800	L	123.6	101.4	9.0	-	-	-	-
1000	L	105.5	85.2	13.9	-	-	-	-
Condition: 1875F (5 min) AC + 1100F (8 hrs)								
RT	L	168.4	151.5	12.3	3.3	-	-	-
RT	T	160.0	144.6	10.0	3.3	-	-	-

(continued)

(Table 2 - concluded)

Sheet 3

Test Temp, F	Dir	UTS, Ksi	YS(0.2%), Ksi	Elong(2"), %	MBR, T	Notch Properties *		
						K_t	NTS, Ksi	NSR
0.080", V-155SM, A-5473, Sheet No. 3 -								
Condition: 1825F (5 min) AC + 1100F (8 hrs)								
-320	L	232.6	219.0	12.0(1)	-	3.0	268.8	1.15
-320	L	-	-	-	-	6.0	235.3	1.01
-110	L	182.5	167.5	12.0(1)	-	3.0	208.2	1.14
-110	L	-	-	-	-	6.0	200.1	1.10
RT	L	157.8	148.1	16.3	2.5	3.0	185.5	1.15
RT	T	148.8	140.3	13.0	2.5	-	-	-
RT	L	160.9	146.1	18.5(1)	-	6.0	173.1	1.08
800	L	116.3	94.0	11.4	-	-	-	-
1000	L	97.3	80.7	17.3	-	-	-	-
Condition: 1850F (5 min) AC + 1100F (8 hrs)								
-320	L	238.2	224.3	10.0(1)	-	3.0	268.8	1.13
-320	L	-	-	-	-	6.0	239.2	1.00
-110	L	182.5	166.4	5.0(1, 2)	-	3.0	206.4	1.13
-110	L	-	-	-	-	6.0	198.5	1.09
RT	L	162.6	149.0	16.0	3.0	3.0	191.2	1.14
RT	T	151.5	142.4	14.0	2.8	-	-	-
RT	L	167.7	150.7	17.8(1)	-	6.0	180.6	1.08
800	L	118.9	95.7	10.5	-	-	-	-
1000	L	103.9	84.2	14.0	-	-	-	-
Condition: 1875F (5 min) AC + 1100F (8 hrs)								
RT	L	165.0	148.1	14.3	3.5	-	-	-
RT	T	154.0	141.0	13.3	3.3	-	-	-

(*) Notch Specimen - 0.500" gage width, 0.250" notch width
for K_t = 3.0, notch radius = 0.020"
for K_t = 6.0, " " = 0.005"

NTS - Notch Tensile Strength
NSR - Notch-Unnotched Strength Ratio
(1) Elongation measured in 1-in gage length specimen.
(2) Broke at end of gage length.
(3) Unnotched specimens broke at extensometer grip; UTS, NTS, and NSR not valid.

$$E = \frac{4\,d\;L^2\;fr^2}{g}$$

where E = dynamic elastic modulus, psi.
d = density, lb/cu in.
L = length, in.
fr = resonant frequency, cycles/sec.
g = gravitational accelaration, in/sec/sec.

Results of these early measurements on annealed material, as listed below, show that Ti-8Al-1Mo-1V possesses a higher modulus and lower density than most other titanium alloys.

	Density lb/cu in	Dir	Temp., F	E 10^6 psi
Bar (5/8" dia)	0.158		RT	19.12
			716	16.45
Sheet (0.070")	0.158	L	RT	17.76
		T	RT	19.22

Since sizeable quantities of Ti-8Al-1Mo-1V sheet are being produced on the Titanium Sheet Rolling Program, additional dynamic modulus measurements were made by Armour Research Foundation at both room and elevated temperatures on recent material. The specimens were laboratory re-annealed at 1450F (4 hrs) which closely simulates the mill annealing treatment being used on Ti-8Al-1Mo-1V in the contract. Corresponding elastic modulus data were also obtained from standard tensile tests for many of the conditions used. Results, which are listed in Tables 3 and 4, show that modulus of elasticity values were obtained which again are higher than exhibited by most other titanium alloys. Where comparisons are available between dynamic and static determinations, it is seen that the dynamic values were generally somewhat higher and no doubt more accurate, since modulus determinations from normal tensile tests are not as precise, particularly at elevated temperatures. Although not tabulated, density values obtained on the two thicker sheets in Table 3 were 0.158-0.159 lb/cu in.

TABLE 3 ELEVATED-TEMPERATURE ELASTIC MODULUS AND TENSILE PROPERTIES OF Ti-8Al-1Mo-1V SHEETS (Laboratory re-annealed at 1450F (4 hrs) FC; averages of duplicate tests unless otherwise noted)

Test Temp, F	Dir	UTS, Ksi	YS(0.2%), Ksi	Elong(2"), %	Elastic Modulus, E, Static 10^3 Ksi	Elastic Modulus, E, Dynamic* 10^3 Ksi
0.020", M-9519, A-3699 Sheet No. 2, Orig. Mill Annealed 1350F (8 hrs) -						
RT	L	145.9	138.4	16.5	17.5	
"	T	145.6	138.2	14.8	18.1	
200	L	132.2	128.2	4.0(1)	17.3	
"	T	135.3	127.3	9.0	16.3	
400	L	122.3	110.3	15.5	15.3	
"	T	118.5	110.2	8.0(1)	15.9	
600	L	111.4	92.0	14.0	15.2	
"	T	113.0	96.3	11.5	15.5	
800	L	103.0	84.0	16.0	12.9	
"	T	103.7	86.5	14.0	14.2	
1000	L	86.5	69.7	18.0	10.6	
"	T	82.7	68.8	20.5	11.1	
0.062", M-9519, A-3713 Sheet No. 3, Orig. Mill Annealed 1350F (8 hrs) -						
RT	L	148.9	139.4	17.0	17.5	18.11
"	T	148.3	138.3	15.8	18.2	19.12
200	L	139.8	127.1	15.8	17.4	
"	T	143.9	129.7	16.3	18.2	
400	L	125.4	109.5	14.5	15.1	16.47
"	T	130.5	113.8	14.5	17.3	17.48
600	L	116.2	97.5	12.0	15.3	
"	T	119.8	99.8	13.5	15.4	16.43
800	L	108.0	88.6	14.0	15.1	
"	T	112.5	91.3	13.5	15.4	
1000	L	88.2	72.8	20.0(1)	12.3	
"	T	92.2	75.4	19.5	9.9	
0.096", M-9519, A-3700 Sheet No. 4, Orig. Mill Annealed 1350F (8 hrs) -						
RT	L	140.3	133.3	18.5	17.2	17.41
"	T	140.2	132.5	18.0	18.2	18.22
200	L	131.1	120.1	17.3	16.9	
"	T	131.3	120.3	16.5	17.0	
400	L	118.0	102.8	15.3	16.4	15.99
"	T	116.7	103.0	14.3	16.2	16.84
600	L	107.4	88.8	16.0	14.4	14.88(2)
"	T	106.1	90.8	13.5	15.8	15.84(3)

(continued)

(Table 3 - concluded)

Test Temp, F	Dir	UTS Ksi	YS(0.2%), Ksi	Elong(2"), %	Elastic Modulus, E, Static 10^3 Ksi	Elastic Modulus, E, Dynamic* 10^3, Ksi
800	L	101.0	82.7	17.8	13.4	
"	T	100.1	84.2	17.3	13.5	
1000	L	83.1	69.6	22.0	13.5	13.13
"	T	83.7	69.0	22.5	13.2	13.93(4)

* A-3713 Sheet No. 2 used for 0.062in dynamic modulus measurements, a sheet from the same group as used for the tensile tests. Dynamic values are averages of duplicate tests except for single T test at 600F (16.43 x 10^3 Ksi) and single tests on A-3700 Sheet No. 4 at 1000F.

(1) Broke at end of gage length.
(2) Actual test temperature 624F.
(3) Actual test temperature 622F.
(4) Actual test temperature 1031F.

TABLE 4 DYNAMIC ELASTIC MODULUS OF Ti-8Al-1Mo-1V AT ROOM TEMPERATURE
(Results of duplicate tensile tests and single modulus determinations)

Heat Treatment	Dir	UTS, Ksi	YS(0.2%), Ksi	Elong (2") %	Dynamic Elastic Modulus 10^3 Ksi
0.096", M-5513, A-3700 Sheet No. 4, Orig. Mill Annealed 1350F (8 hrs) -					
1800F (5 min) AC + 1100F (8 hrs)	L	141.9	133.2	14.3	17.55
" "	T	141.3	131.4	16.5	17.98
1850F (5 min) AC + 1100F (8 hrs)	L	149.6	139.2	14.5	17.64
" "	T	147.5	134.2	16.5	18.10
0.080", V-1555M, A-5473 Sheet No. 3, Orig. Mill Annealed 1450F (4 hrs) -					
1800F (5 min) AC + 1100F (8 hrs)	L	157.8	148.1	16.3	19.13
" "	T	148.8	140.3	13.0	18.23
1850F (5 min) AC + 1100F (8 hrs)	L	162.6	149.0	16.0	19.16
" "	T	151.5	142.4	14.0	18.22

Of the elevated-temperature dynamic data listed in Table 3, the results from the thicker 0.096in sheet (A-3700 Sheet No. 4) are considered to be more accurate because of the thicker specimens used. However, dynamic results from the two sheets at room temperature are only in fair agreement with the 0.062in material possessing 0.7 - 0.9 x 10^3 Ksi higher modulus. This difference may be due to the variance in precision of measurements between the two sheets or it may be that the modulus is a function of rolling texture. Additional studies would be required to answer these questions.

Table 3 shows the normal decrease in strength and elastic modulus with increased testing temperature. It is of interest to note that at 600F the modulus has only dropped to about 15.0 - 16.0 x 10^3 Ksi and at 1000F values in excess of 13.0 x 10^3 Ksi were observed.

The effect of a difference in duplex annealing on the dynamic modulus of two Ti-8Al-1Mo-1V sheets is shown in Table 4. Raising the solution temperature in the duplex cycle from 1800 to 1850F had little effect on the modulus; if anything, the modulus of elasticity increased very slightly. The modulus of the 0.080in sheet in Table 4 was somewhat higher than the 0.096in material; again, this may be the result of differences in texture. Also, there is a reversal of L and T between the two sheets and this, no doubt, is due to the reverse directionality obtained in the 0.080in sheet as a result of an unbalance between the last two stages of cross rolling(3). Comparing room-temperature dynamic modulus values of the 0.096in sheet in Tables 3 and 4, it is seen that, by duplex annealing, the longitudinal values increased and the transverse values decreased about 0.2 x 10^3 Ksi compared to the 1450F (4 hrs) FC annealed material. In other words, duplex annealing decreased the directionality in modulus even though the directionality in strength was virtually unaffected.

Creep and Stability Properties

Creep-stability tests were performed at 800 and 1000F on duplex annealed specimens from several sheets of Ti-8Al-1Mo-1V, the

same material as was used for the tensile and bend evaluation listed in Tables 1 and 2. In addition, both thermal (without stress) and creep-stability tests were conducted on mill annealed and duplex annealed samples from the 0.080in sheet; temperatures for the exposures without stress were from 800 - 1200F, while the creep-stability exposures covered the range, 800 - 1100F. Results of this study are presented in Table 5.

As shown in earlier work for creep exposure at 1000F[1], duplex annealing at 1850F (5 min) AC + 1100F (8 hrs) produced superior creep resistance compared to the 1825F (5 min) AC + 1100F (8 hrs) duplexing cycle. The same trend was also true for creep testing at 800F, although the differences were not as pronounced for the 0.080in sheet (A-5473 Sheet No. 3) as for the other sheets. Of particular interest is the superior creep resistance provided by duplex annealing compared to the mill annealed condition (0.080in sheet); however, it should be noted that this sheet was mill annealed at 1450F (4 hrs) and, as a result, has previously been shown to possess inferior 1000F creep properties in this condition[3]. Even so, the advantage of duplex annealing over the range, 800 - 1100F, is obvious.

Good stability, as judged by as-exposed tensile elongation, was generally obtained in both sheets from M-9519 (0.020 and 0.096in), although acid pickling 0.003in from the thickness after 1000F creep exposure improved the ductility. This indicates some degree of surface instability in duplex annealed material as exposed under stress for 150 hours at 1000F.

Stability of the other three sheets, which had been originally mill annealed at 1450F (4 hrs), at 1000F was definitely inferior as exposed, although, in all instances, the tensile ductility was restored by acid pickling 0.003in from the specimen thickness after exposure. Thus, metallurgical stability was achieved during stressed exposure of duplex annealed specimens at 800 - 1100F. Reasons for the loss in tensile elongation as-creep exposed are not completely understood, since so much prior data have indicated surface stability

TABLE 5 THERMAL AND CREEP-STABILITY PROPERTIES OF Ti-8Al-1Mo-1V SHEETS

Heat Treatment	Dir	Stability Exposure Temp, F	Stability Exposure Stress Ksi	Stability Exposure Time, Hrs	Stability Exposure Creep Def, %	UTS, Ksi	YS (0.2%), Ksi	Elong (1 in), %
M-8519, 0.020in (S-1807, mill annealed 1400/1450F - 8 hrs)								
1825F (5 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	163.5	147.3	11.0
	L	800	61.2	150	0.24	176.7	171.8	9.0
	L	1000	25.8	150	0.41	168.9	160.9	7.0(1)
	L	1000	25.3	150	0.47	166.1	137.3	13.0(2)
1850F (5 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	173.0	151.9	8.0
	L	800	65.5	150	0.07	165.8	149.7	8.5(1)
	L	1000	21.9	150	0.16	171.1	167.9	1.0
	L	1000	21.6	150	0.16	173.4	167.3	5.0(2)
V-1554M, 0.025in (A-5491, Sheet No. 1, mill annealed 1450F - 4 hrs)								
1825F (5 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	171.6	158.4	14.0
	L	800	65.4	150	0.12	169.3	155.2	6.0
	L	1000	25.1	150	0.68	136.7	(1, 3)	(1, 3)
	L	1000	25.7	150	0.89	163.4	145.2	10.0(2)
1850F (5 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	173.9	158.0	15.5
	L	800	66.3	150	0.13	173.7	158.8	8.0
	L	1000	22.1	150	0.48	121.5	(1, 3)	(1, 3)
	L	1000	25.3	150	0.37	169.8	152.7	13.0

(continued)

Table 5 - continued

Sheet 2

Heat Treatment	Dir	Stability Exposure Temp, F	Stability Exposure Stress Ksi	Stability Exposure Time, Hrs.	Stability Exposure Creep Def, %	UTS, Ksi	YS (0.2%), Ksi	Elong. (1 in) %
V-4535B, 0.050in (A-5473, Sheet No. 2, mill annealed 1450F - 4 hrs)								
1825F (7 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	170.5	155.1	16.0
	L	800	63.9	150	0.09	165.1	152.3	8.0(1)
	L	1000	24.1	150	0.94	163.4	-	1.5(1)
	L	1000	24.9	150	0.91	169.2	156.2	18.0(2)
1850F (3 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	172.0	155.5	15.0
	L	800	64.1	150	0.04	162.9	148.3	5.0(1)
	L	1000	25.5	150	0.32	154.6	153.6	1.5
	L	1000	26.1	150	0.37	174.3	157.4	17.5(2)
V-1555M, 0.080in (A-5473, Sheet No. 3, mill annealed 1450F - 4 hrs)								
As Mill Annealed	L	Not Exposed		-	-	159.1	147.4	18.0
	L	800	-	100	-	154.5	148.8	6.0
	L	800	-	100	-	159.4	147.1	19.0(2)
	L	800	65.1	150	0.34	161.7	142.5	18.0
	L	800	64.9	150	0.37	158.9	142.4	17.0(2)
	L	900	-	100	-	154.1	151.2	6.0
	L	900	-	100	-	161.4	150.8	14.0(2)
	L	900	45.5	150	1.05	163.4	143.1	13.0
	L	900	44.4	150	0.78	160.5	143.7	19.0(2)
	L	1000	-	100	-	-	152.9	1.0(4)
	L	1000	-	100	-	161.8	152.1	16.0(2)
	L	1000	25.0	150	2.27	157.3	149.0	4.5
	L	1000	24.9	150	2.69	164.3	145.9	15.5(2)
	L	1100	-	100	-	151.6	149.4	2.0
	L	1100	-	100	-	159.4	149.8	18.0(2)
	L	1100	10.0	150	4.77	155.9	151.3	3.0
	L	1100	9.9	150	4.87	162.6	150.9	10.0(2)
	L	1200	-	100	-	150.0	145.8	3.0(1)
	L	1200	-	100	-	159.4	147.8	16.0(2)

continued

Table 5 - continued

Sheet 3

Heat Treatment	Dir	Stability Exposure: Temp, F	Stress Ksi	Time, Hrs	Creep Def, %	UTS, Ksi	YS (0.2%) Ksi	Elong (1 in) %
[illegible], [illegible].080in (cont'd)								
	L	Not Exposed		-	-	160.8	145.7	17.5
[illegible]F ([illegible] min) AC + 1100F (8 hrs)	L	800	33.5	150	0.11	154.9	146.9	4.0
	L	1000	24.3	150	0.57	150.1	149.5	2.0
	L	1000	25.3	150	0.67	165.3	149.4	18.0(2)
	L	Not Exposed		-	-	167.7	150.7	17.5
	L	800	-	100	-	157.6	141.9	20.0
	L	800	-	100	-	155.7	141.4	18.0(2)
	L	[illegible]	34.9	150	0.13	162.2	146.6	8.0
	L	800	34.9	150	0.39	161.9	142.4	14.0
	L	800	35.[illegible]	150	0.14	159.8	139.7	15.0(2)
	L	800	-	100	-	155.6	144.3	11.0
	L	900	-	100	-	159.4	145.0	20.0(2)
	L	900	44.[illegible]	150	0.27	158.2	143.8	9.0(1)
	L	900	45.[illegible]	150	0.28	162.7	141.9	18.0(2)
1650F ([illegible] min) AC + 1100F (8 hrs)	L	1000	-	100	-	151.2	146.9	3.0
	L	1000	-	100	-	161.0	145.6	20.5(2)
	L	1000	24.[illegible]	150	0.37	158.3	149.5	3.0
	L	1000	25.[illegible]	150	0.43	139.3	152.8	15.5(2)
	L	1000	24.9	150	0.38	153.2	148.2	6.0
	L	1000	24.9	150	0.33	161.3	143.8	13.5(2)
	L	1100	-	100	-	154.4	143.1	18.0
	L	1100	-	100	-	-	-	-
	L	1100	9.9	150	2.74	155.1	150.3	3.5
	L	1100	10.[illegible]	150	1.82	165.4	148.2	17.0(2)
	L	1200	-	100	-	145.1	142.4	3.0
	L	1200	-	100	-	160.1	146.8	18.0(2)

(concluded next page)

Table 5 - concluded

Sheet 4

Heat Treatment	Dir	Stability Exposure Temp, F	Stability Exposure Stress Ksi	Stability Exposure Time, Hrs	Creep Def, %	UTS Ksi	YS (0.2%) Ksi	Elong. (1 in) %
M-9519, 0.096in (A-3700, Sheet No. 4 - mill annealed 1350F - 8 hrs)								
1825F (5 min) AC + 1100F (8 hrs)	L	Not Exposed		-	-	144.3	133.1	19.0
	L	800	65.5	150	0.21	147.3	135.6	19.0
	L	1000	25.3	150	0.51	148.9	139.1	19.0
	L	1000	25.2	150	0.39	153.1	143.8	16.0(2)
1850F (5 min) AC + 1100F (8 hrs)	L	NotExposed		-	-	152.0	137.0	18.5
	L	800	65.9	150	0.12	156.4	141.1	21.0
	L	1000	25.2	150	0.30	154.2	141.0	11.0
	L	1000	25.1	150	0.19	156.7	145.4	16.5(2)

(1) Broke at end of gage length.
(2) Acid pickled 0.003in from gage after creep exposure, but prior to tensile testing at room temperature. All others tensile tested as-exposed with no surface conditioning.
(3) Broke before yield stress.
(4) Broke in pin grip.

at 1000F [1,2]. Many of the specimens listed in Table 5 broke at the end of the gage length and a few of them may have suffered some incidental stress corrosion damage, although the latter was certainly not obvious during subsequent examination of the specimens.

Mill annealed (1450F - 4 hrs) specimens exhibited good metallurgical stability over the range of 800 - 1000F with the possibility of some instability at 1100F. Surface instability was observed in mill annealed samples exposed at 1000 and 1100F, while good as-exposed elongation values were obtained after creep exposure at 800 and 900F. Except for the latter two temperatures, the creep deformation levels were greater than 2.27 percent and this may have had some bearing on the subsequent elongation. Tensile elongation of mill annealed specimens exposed to 800 - 1200F for 100 hours without stress also suffered unless the samples were acid pickled after exposure; likewise, this was contrary to all previous results. Companion specimens, which had been duplex annealed, exhibited good as-exposed ductility after storage at 800, 900, and 1100F, but relatively poor elongations after exposure to 1000 and 1200F. However, in every instance, nearly all of the ductility was restored by pickling 0.003in from the gage after exposure.

Reviewing the properties of duplex annealed Ti-8Al-1Mo-1V sheet specimens, it is seen that there are very few differences between annealing at 1800, 1825, and 1850F (followed by stabilizing at 1100F for 8 hrs) except for creep resistance. This property alone gives a clear-cut advantage to 1850F (5 min) AC + 1100F (8 hrs), since the creep properties improve markedly with increasing solution temperature. Therefore, to be sure of achieving the best possible creep resistance and still safely be below the beta transus, future duplex annealing of Ti-8Al-1Mo-1V will be performed at 1850F (5 min) AC + 1100F (8 hrs). Although establishment of property specifications for this condition cannot adequately be made until full size sheets are duplex annealed and tested, it seems reasonable that 130 Ksi YS, 140 Ksi UTS, 10 percent Elong., and 4T bend radius could be achieved.

Contamination and Protection of Ti-8Al-1Mo-1V Sheet During Duplex Annealing

Having reached the conclusion that duplex annealing Ti-8Al-1Mo-1V sheet at 1850F (5 min) AC + 1100F (8 hrs) is optimum for providing good 1000F creep resistance, consideration was given to the question of contamination which would occur during such a heat treatment in air. Of course, a certain amount of surface conditioning after heat treatment would be necessary; at a minimum, this would entail descaling and pickling, and might also involve surface grinding.

To determine the extent of the contamination during duplex annealing and to minimize it, a limited investigation was undertaken to measure the effects of contamination by metallographic examination and bend testing, and to evaluate several available protective coatings. For this, 1 x 6in longitudinal strips were cut from an 0.062in sheet of Ti-8Al-1Mo-1V (M-9519, A-3713, Sheet No. 3) which had been mill annealed at 1350F (8 hrs). Duplicate samples were duplex annealed at 1850F (5 min) AC + 1100F (8 hrs), with and without previously applying a protective coating and, for those annealed without a coating, various amounts were removed by acid pickling after the solution treatment at 1850F prior to stabilization at 1100F. A small portion of each was then sheared off for microscopic examination while the balance of each strip was press brake bend tested to obtain a minimum satisfactory bend radius as examined under 20-power magnification.

Conditions studied and results of bend tests are listed in Table 6, showing that none of the protective coatings offered substantially more protection against oxidation then uncoated material, based on a minimum amount of gage removal by acid pickling after heat treatments. In uncoated samples, descaling after the 1850F treatment (no pickling), followed by acid pickling 0.002in from the gage after the 1100F (8 hrs) stabilization cycle, resulted in a minimum bend radius of 4.0T, a value that was not duplicated by any of the protected specimens after descaling and acid pickling 0.002in from the gage. Only by excessive pickling of 0.006in was the bendability markedly improved in a few of the protected

TABLE 6 EFFECTS OF PROTECTIVE COATINGS AND PICKLING ON THE MINIMUM BEND RADIUS OF DUPLEX ANNEALED Ti-8Al-1Mo-1V SHEET (M-9519, A-3713, Sheet No.3, 0.062", Longitudinal Samples)

Protective Coating	Treatment	Minimum Bend Radius, T*			
		No Pickle	Pickle 0.002"	Pickle 0.004"	Pickle 0.006"
None	1850F (5 min) AC + 1100F (8 hrs)	5.4f(1)	-	-	-
None	1850F (5 min) AC + Descale and Pickle + 1100F (8 hrs) + 0.002" pickle	4.0	4.0	4.5	4.0
Turco 4367	Coat + 1850F (5 min) AC + 1100F (8 hrs) + Descale and Pickle	9.0	4.3	4.0	2.8
Ti-Form II	" " " " "	7.6f(1)	5.0	3.5	3.6
Markal CRT-B	" " " " "	6.1f(1)	4.6	4.0	2.8
DuPont J-400	" " " " "	9.5f(1)	5.1f(1)	4.0	3.5
Al-Tex	" " " " "	8.0f(1)	4.4	4.0	4.0
A-418	" " " " "	7.6f(1)	4.2f(1)	4.0	3.6

(*) No pickle designates that samples were descaled only in Virgo; all bend specimens examined and rated on basis of a magnification of 20 times.

(1) f - designates fracture at specified radius; minimum bend radius not established because of lack of sample material.

specimens after descaling and acid pickling 0.002in from the gage. Only by excessive pickling of 0.006in was the bendability markedly improved in a few of the protected samples; i.e., those coated with Turco 4367 and Markal CRT-B.

Microstructures near the edge of two unprotected specimens are depicted in Figures 1 and 2. Figure 1 shows the depth of contamination of a duplex annealed-and-descaled sample (no acid pickling) to be approximately 0.002-0.0025in. Figure 2 illustrates the sheet cross section after pickling 0.002in from each surface; it is seen that substantially all of the contamination has been removed.

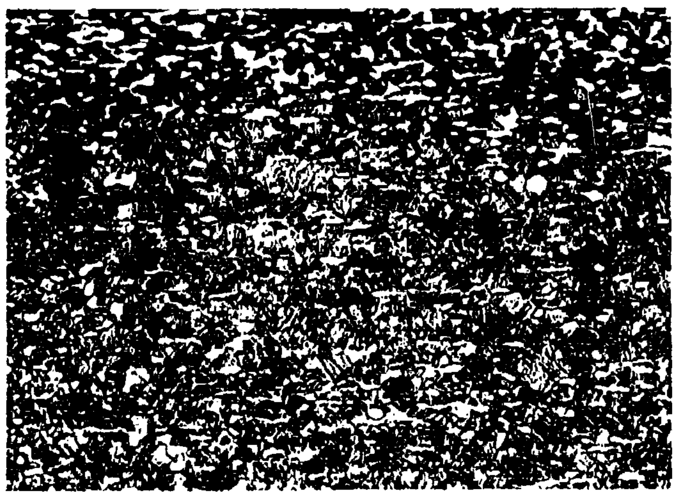
As a result of this phase of investigation, it is concluded that none of the coatings utilized offers sufficient protection to warrant the additional effort of incorporating them into the 1850F (5 min) AC + 1100F (8 hrs) duplex annealing cycle. Results of bend tests and metallographic examination show that descaling and pickling or grinding 0.002in from gage after 1850F (5 min) AC plus grinding and/or pickling 0.002 - 0.003in from gage after stabilization at 1100F (8 hrs) should be adequate to remove all contamination encountered during duplex annealing.

With the results of the preceding laboratory studies as a basis, 12 sheets of Ti-8Al-1Mo-1V from the first ingot, M-9519, will be duplex annealed at 1850F (5 min) AC + 1100F (8 hrs). Four sheets of each of three gages, 0.020, 0.062, and 0.096in gage (nominal 36 x 96in), will be cleaned, heated at 1850F (5 min) AC in a roller hearth furnace, descaled and pickled, stabilized at 1100F (8 hrs), and then finish ground, pickled, and tested. This development program will be conducted during the next period.

The study of the effect of hydrogen on mill annealed and duplex annealed Ti-8Al-1Mo-1V sheet, which was outlined in the Ninth Bimonthly Report(3), is nearing completion with at least preliminary results becoming available during the next report period. An additional welding investigation is also in progress, but it probably will not be completed until after the next period.

61-110-AA Kroll Etch 250X

FIGURE 1 Ti-8Al-1Mo-1V SHEET, M-9519, A-3713 SHEET No. 3, LONGITUDINAL SECTION, 1850F (5 min) AC + 1100F (8 hrs) + DESCALE (NO PICKLING). DEPTH OF CONTAMINATION 0.002-0.0025in.



61-110-AC Kroll Etch 250X

FIGURE 2 Ti-8Al-1Mo-1V SHEET, M-9519, A-3713 SHEET No. 3, LONGITUDINAL SECTION, 1850F (5 min) AC + DESCALED AND PICKLED 0.001in FROM EACH SURFACE + 1100F (8 hrs) + ACID PICKLED 0.001in FROM EACH SURFACE. SUBSTANTIALLY ALL CONTAMINATION HAS BEEN REMOVED.

PROCESSING OF Ti-8Al-1Mo-1V

Sheet Processing

As indicated in the Tenth Bimonthly Report[4], plans were made to duplex anneal half of the Ti-8Al-1Mo-1V sheets, although delivery of material in this condition is subject to change. However, at a Titanium Alloy Sheet Rolling Program Meeting in Washington, D. C., on 15 March 1961, a firm decision was made to delete the solution treat-and-age condition from the program. Based on the premise that only half of the sheets would be finished as mill annealed, the 92 sheets from the five 1600-pound ingots, V1551- V1555, were rough ground and then 50 percent of each gage was held for duplex annealing, pending the results to be obtained from the 12 sheets described in the previous section. Finishing operations were continued on the other half (46 sheets), consisting of finish grinding, pickling, and testing. Grinding and pickling were completed on this latter group, although testing of a few sheets remains.

The ranges of tensile and bend properties obtained through this period are listed in Table 7, showing that good strengths and ductility values were obtained. Some reverse directionality was observed, particularly in the 0.040, 0.062, and 0.090in sheets; this phenomenon has been discussed previously[3] and since approximately the same rolling schedule was used on the sheets in Table 7 as had been used on the first 30 sheets (see Table 1, Ninth Bimonthly Report), no doubt the reverse directionality is due to the second stage of cross rolling being heavier than the third stage.

Comparing the strengths in Table 7 with those in Table 1 of the Ninth Bimonthly Report, it is seen that annealing at 1450F for 8 instead of 4 hours has decreased the strengths 5 - 10 Ksi. As a result, a more realistic automatic release specification appears to be:

130 Ksi min YS (0.2%)
140 Ksi min UTS
10% min Elong
4.0T max Bend Radius
150 ppm max H_2

TABLE 7 RANGE OF TENSILE AND BEND PROPERTIES OF 36 Ti-8Al-1Mo-1V SHEETS MILL ANNEALED AT 1450F (8 hrs). (Mill processed and tested)

Gage, in	No. of Sheets	Dir	Range of Properties: UTS, Ksi	YS(0.2%), Ksi	Elong (2"), %	Bend Radius, T	H_2, ppm
0.020	8	L	141-154	133-145	12.5-20	3.0	60-90
		T	142-152	135-143	13.5-20	3.0	
0.040	9	L	151-159	140-149	12-17	3.1-3.3	50-150
		T	143-148	132-139	13-16	3.1-3.3	
0.062	8	L	149-157	137-145	12-17.5	3.1-3.2	50-150
		T	144-148	134-138	12-16.5	3.1-3.5	
0.090	5	L	155-156	145-148	15.5	3.1	70-80
		T	143-147	136-138	15-17	3.1-3.3	
0.125	6	L	148-152	143-146	12-18	3.0-3.2	30-40
		T	152-155	141-146	15.5-18	3.2-4.0	

This specification will be recommended to the Navy Bureau of Weapons.

After the sheets have been inspected for satisfactory surface conditions, one 0.062in sheet will be used for a uniformity study of properties similar to that performed on earlier sheets[2]. Included will be tensile, bend, and creep-stability tests throughout the sheet.

Because the 46 sheets, which had been designated for duplex annealing, would not have been evaluated on the basis of mill annealed properties at final testing, a longitudinal strip was sheared from each rough ground sheet, laboratory acid pickled to remove 0.004in from gage, and then tensile and bend tested at room temperature. Although this procedure provided only longitudinal test results, it was considered to be a compromise between obtaining at least some mill annealed properties on this group and conserving material. Ranges of longitudinal tensile and bend properties for each gage are presented in Table 8 and compare favorably with the longitudinal property ranges listed in Table 7. Strengths in the latter tabulation were about 3-5 Ksi higher for the 0.020 and 0.062in gages while the 0.090 and 0.125in sheets were 2-10 Ksi lower in strength. However, these differences are not considered to be significant in view of the fact that the specimens in Table 8 were cut from only partially finished sheets. One 0.062in sheet, which was damaged during grinding, was scrapped; therefore, Table 8 covers only 45 instead of the original 46 sheets.

Based on the properties given in Table 8, these 45 sheets would meet the automatic release property specification described above except for two 0.125in sheets which possessed a 4.2T bend radius. However, since many of the strips sheared from the 45 sheets contained the normally-encountered edge defects, test strips cut after final processing would probably pass the proposed 4.0T bendability requirement.

TABLE 8 RANGE OF MILL ANNEALED LONGITUDINAL TENSILE AND BEND PROPERTIES OF 45 Ti-8Al-1Mo-1V SHEETS (Mill annealed at 1450F for 8 hrs and rough ground; longitudinal strips were sheared and 0.004" removed from gage before testing)

Gage, in	No. of Sheets	Range of Longitudinal Properties			
		UTS, Ksi	YS(0.2%), Ksi	Elong, 2", %	Bend Radius, T
0.020	12	146-163	138-151	12-18	2.4-3.0
0.040	12	148-158	142-148	12-18	2.8-3.2
0.062	7	149-157	141-148	14.5-16.5	3.2-3.5
0.090	7	145-153	136-141	14-18	2.8-3.3
0.125	7	147-149	142-144	14-17.5	3.1-4.2

Ingot Processing

A sixth ingot of Ti-8Al-1Mo-1V, V-1848, was melted to serve as replacement material for the 30 sheets, which were removed from the program because they had been mill annealed at 1450F for only 4 hours. This heat (1740 lbs) was pressed to 2-7/8 x 12in slabs from 2050F with reheating at 1950F, conditioned, and sampled for chemistry at various ingot locations. Chemical analyses, which are listed in Table 9, show that the composition of V-1848 is quite satisfactory and that good chemical uniformity exists from top to bottom.

Following slab conditioning and chemical analysis, processing of 26 sheets was scheduled from V-1848 along with 6 sheets from sheet bars remaining from V-1552, V-1553, and V-1554. These 32 sheets will be finish rolled from 1800F, mill annealed at 1450F (8 hrs), and finish ground and pickled using the same procedures as for the first five ingots. However, the second and third stages of cross rolling will be better balanced to minimize the reverse directionality previously encountered. Much of this processing will be performed during the next report period. A schedule of the number and gages of sheets from V-1848 and other sheet bars is as follows:

No of Sheets	Gage, in	Ingot and Location
9	0.020	V-1848T
3	0.020	V-1552B
3	0.040	V-1848T
1	0.040	V-1552T
1	0.040	V-1554T
10	0.062	V-1848B
2	0.090	V-1848M
1	0.090	V-1553T
2	0.125	V-1848M

With the additional sheet processing listed above, a general status of the production of Ti-8Al-1Mo-1V sheets is tabulated below:

TABLE 9 CHEMICAL ANALYSES OF Ti-8Al-1Mo-1V INGOT, V-1848
(Samples from 2-7/8 x 12in slab slices)

Ingot Location	Chemical Analyses, %						
	Al	Mo	V	Fe	C	N_2	O_2
Top	7.83	1.12	1.04	0.12	0.020	0.026	0.068
Top Middle	7.91	1.09	1.03	0.12	0.032	0.025	- - -
Bottom Middle	7.91	1.14	0.97	0.11	0.032	0.026	- - -
Bottom	7.86	1.13	1.01	0.10	0.026	0.024	0.080
Average	7.88	1.12	1.02	0.11	0.028	0.025	0.074

Status of Ti-8Al-1Mo-1V Sheets

Gage, in	Number of Sheets: Ordered	In Process	Completed and Tested
0.020	27	36	8
0.040	20	29	9
0.062	18	26	8
0.090	15	17	5
0.125	14	16	6
Total	94	124	36

In addition to the 36 sheets specified as being completed and tested, there are 9 which have completed processing but have not been tested and 45 (Table 8) which have been rough ground and are being held for duplex annealing. Mill processing and testing of this large number of Ti-8Al-1Mo-1V sheets will be continued during the next period.

EVALUATION OF Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr SHEETS

Results of evaluation of the initially-rolled sheets of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, which were discussed in the Eighth[1] and Ninth[3] Bimonthly Reports, permitted the selection of 1750F as the optimum finish rolling temperature for both alloys. However, the optimum final annealing temperature had not been established and additional creep-stability testing was deemed necessary before the annealing cycle could be chosen. The Tenth Bimonthly Report[4] outlined the scope of this additional stability testing and results of this phase of the study, along with data from a preliminary welding investigation, are described in the sections to follow.

Effect of Annealing Variables on Creep and Stability of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheets

Initial sheets of both alloys (V1540 and V1541) finish rolled from

1750F were used for this investigation along with the three sheets of Ti-7Al-12Zr finish rolled from 1800F to be sure the program was sufficiently comprehensive. Also, in a few instances, both stressed and unstressed stability tests were conducted with all exposures being made at 1000F.

Results of the large number of stability tests are listed in Tables 10, 11, and 12. As shown in Table 10, little or no stability problems were encountered in Ti-5Al-5Sn-5Zr, an observation made in previous work on the initial sheets of this composition(3). The major item of interest in Table 10 is the relatively inferior creep resistance exhibited by samples given a simulated mill annealing treatment at 1400-1500F for 4 hours followed by furnace cooling compared to the simple annealing cycles (air cooled) in the alpha field. As the simulated mill annealing temperature was raised from 1400 to 1500F, the creep deformation at 1000F decreased, but, even after 1500F (4 hrs) FC, the creep deformation was considerably higher than after annealing at 1650F for 20-30 minutes and air cooling. Comparing the creep properties after annealing at 1650F for 10 and 20 minutes (Table 10) with those obtained after 1650F (30 min) AC (Table 6, Ninth Bimonthly Report), it is seen that there was little difference in 1000F creep resistance between the 20 and 30 minute cycles, although both offered a substantial improvement over the 10 minute annealing treatment.

Therefore, it was concluded that a simple annealing cycle high in the alpha field was superior to a slow cool mill annealing treatment for Ti-5Al-5Sn-5Zr and that 1650F (20-30 min) AC provided improved creep resistance over a 10 minute cycle. Of the two times, 20 and 30 minutes, the latter was selected as optimum and represents somewhat of a compromise between the superior creep resistance offered by annealing times greater than 30 minutes and encountering a minimum of sheet oxidation during annealing periods shorter than 30 minutes. Thus, a finish annealing treatment of 1650F (1/2 hr) AC will be used on all Ti-5Al-5Sn-5Zr sheets produced in the contract.

TABLE 10 EFFECT OF ANNEALING VARIABLES ON THE 1000F CREEP-STABILITY PROPERTIES OF Ti-5Al-5Sn-5Zr SHEETS (Finish rolled from 1750F, mill annealed at 1350F for 8 hrs, and laboratory annealed as indicated; longitudinal specimens from V-1540; creep exposure 1000F - 25 Ksi - 150 hrs)

Gage in	Sheet No.	Annealing Treatment	Creep Def, %	UTS Ksi	YS(0.2%), Ksi	Elong (1"), %
0.020	A-4812	1400F (4 hrs) FC	Not Exp.	125.9	114.0	18.8*
(0.081% O_2,		"	"	122.4	119.0	22.0
45 ppm H_2)		"	0.38	121.2	112.1	20.0
		1450F (4 hrs) FC	Not Exp.	123.8	115.2	19.8*
		"	"	121.7	119.5	19
		"	0.22	118.5	109.8	19 (1)
		1500F (4 hrs) FC	Not Exp.	123.5	117.8	18*
		"	"	119.8	112.9	21.5
		"	0.15	118.7	111.3	20 (1)
		1650F (10 min) AC	Not Exp.	125.0	111.7	22
		"	0.000	123.0	111.1	19
		"	0.059	121.5	114.6	(2, 3)
		1650F (20 min) AC	Not Exp.	121.7	110.0	14 (2)
		"	0.025	119.1	108.5	19
		"	0.056	119.3	104.5	19
0.062	A-4801	1400F (4 hrs) FC	Not Exp.	124.5	117.3	19*
(0.072% O_2,		"	"	125.8	120.0	24
35 ppm H_2)		"	0.26	125.1	114.1	23 (1)
		1450F (4 hrs) FC	Not Exp.	124.2	117.6	19.5*
		"	"	124.1	118.9	21.5
		"	0.25	125.5	117.2	19
		1500F (4 hrs) FC	Not Exp.	124.0	118.6	19.5*
		"	"	123.7	117.5	25
		"	0.072	124.3	114.3	20
		1650F (10 min) AC	Not Exp.	124.3	117.6	19.5
		"	0.072	124.9	115.3	20
		"	0.059	123.8	117.6	19
		1650F (20 min) AC	Not Exp.	123.6	111.4	19.5
		"	0.039	123.9	112.9	22
		"	0.012	130.0	115.2	21

(continued)

(Table 10 - concluded)

Gage in	Sheet No.	Annealing Treatment	Creep Def, %	UTS Ksi	YS(0.2%), Ksi	Elong(1"), %
0.090	A-4814	1400F (4 hrs) FC	Not Exp.	124.2	117.6	19.3*
(0.072% O_2,		"	"	126.2	120.2	23
30 ppm H_2)		"	0.17	125.4	114.8	22
		1450F (4 hrs) FC	Not Exp.	124.0	112.9	19.5*
		"	"	123.8	117.9	24.5
		"	0.18	123.9	117.0	22 (1)
		1500F (4 hrs) FC	Not Exp.	122.8	118.1	17.8*
		"	"	124.6	118.5	24.5
		"	0.081	123.2	116.3	23 (1)
		1650F (10 min) AC	Not Exp.	123.7	111.7	20
		"	0.059	125.4	117.8	20
		"	0.062	123.4	114.3	10 (2, 3)
		1650F (20 min) AC	Not Exp.	123.4	111.1	21.5
		"	0.047	124.2	114.6	22
		"	0.037	123.7	114.5	23

(*) 2in gage length specimens; all others 1-in gage length.

(1) Tensile tested after acid pickling 0.002" from gage of exposed specimen because of evidence of stress corrosion on surface.

(2) Broke at end or outside of gage length.

(3) Stress corrosion evident in fracture.

TABLE 11 EFFECT OF ANNEALING VARIABLES ON THE 1000F CREEP-STABILITY PROPERTIES OF Ti-7Al-12Zr SHEETS (Finish rolled as indicated, mill annealed at 1350F for 8 hrs, and laboratory annealed as noted; longitudinal specimens from V-1541; creep exposure 1000F-25 Ksi-150 hrs)

Gage, in.	Sheet No.	Rolling Temp, F	Annealing Treatment	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong (1"), %
0.020	A-4798	1750	1400F (4 hrs) FC	Not Exp.	145.3	135.2	17.5*
(0.109% O_2,			"	"	137.9	132.4	17.0(1)
78-90 ppm H_2)			"	0.21	121.0	121.0	1.0(2)
			1450F (4 hrs) FC	Not Exp.	140.1	128.0	17.0*
			"	"	137.6	130.6	21.5
			"	0.20	122.6	122.6	2.0(3)
			1500F (4 hrs) FC	Not Exp.	139.2	130.6	17.5*
			"	"	137.2	131.6	21.0
			"	0.13	129.1	129.1	2.0(2)
			1450F (2 hrs) AC	Not Exp.	144.9	134.9	15.0
			"	0.17	143.3	135.9	10.0(1, 4)
			"	0.15	120.6	(5)	0 (4)
(97ppm H_2)			1550F (1 hr) AC	Not Exp.	141.8	131.9	13.0
			"	0.10	139.0	126.2	7.0(4)
			"	0.09	136.3	134.8	6.0(1,3)
(95 ppm H_2)			1650F (1/2 hr) AC	Not Exp.	147.1	133.8	14.0
			"	0.081	133.3	130.8	4.0(4)
			"	0.077	131.4	120.6	11.0(1, 6)
(89 ppm H_2)			1650F (2 hrs) AC	Not Exp.	132.4	123.4	18.0
			"	0.015	114.1	(5)	0 (4)
			"	0.041	129.3	117.3	11.0(6)
(72 ppm H_2)			1750F (1/2 hr) AC	Not Exp.	135.4	128.7	18.0
			"	0.069	129.6	121.9	9.0(4)
			"	0.084	113.9	(5)	0 (2, 3)

(continued)

(Table 11 continued)

Gage, in.	Sheet No.	Rolling Temp. F	Annealing Treatment	Creep Def., %	UTS, Ksi	YS(0.2%), Ksi	Elong (1"), %
0.062	A-4802	1750	1400F (4 hrs) FC	Not Exp.	134.8	124.8	20.5*
(0.091% O_2)			"	"	140.2	132.0	20.5
			"	0.16	132.1	123.8	3.0(2)
(48 ppm H_2)			1450F (4 hrs) FC	Not Exp.	133.2	124.8	19.3*
			"	"	133.1	126.4	23.0
			"	0.12	133.7	122.8	17.0
(54 ppm H_2)			1500F (4 hrs) FC	Not Exp.	134.0	127.0	17.8*
			"	"	132.6	124.7	24.0
			"	0.12	134.2	122.8	10.0
			1450F (2 hrs) AC	Not Exp.	137.2	128.2	16.5
			"	0.09	139.4	130.6	18.0
			"	0.21	140.8	129.8	18.0
			1550F (1 hr) AC	Not Exp.	135.8	125.0	17.0
			"	0.072	136.9	127.8	7.0(4)
			"	0.019	132.7	120.9	8.0(4)
(34 ppm H_2)			1650F (1/2 hr) AC	Not Exp.	134.3	124.1	15.0
			"	0.050	134.4	121.1	11.0
			"	0.061	131.4	119.8	8.0(2)
(36 ppm H_2)			1650F (2 hrs) AC	Not Exp.	128.3	122.9	23.0
			"	0.012	130.5	118.0	20.0
			"	0.036	129.7	117.7	10.0(2)
(33 ppm H_2)			1750F (1/2 hr) AC	Not Exp.	131.1	122.3	22.5
			"	0.057	130.9	121.5	18.0
			"	0.077	131.3	118.9	21.0
0.090	A-4809	1750	1400F (4 hrs) FC	Not Exp.	140.2	128.7	19.8*
(0.073% O_2)			"	"	141.3	131.2	21.0
			"	0.14	141.6	129.5	12.0(4)
(43 ppm H_2)			1450F (4 hrs) FC	Not Exp.	137.3	126.3	18.0*
			"	"	138.5	129.7	17.5
			"	0,12	139.2	125.3	17.0(6)
(45 ppm H_2)			1500F (4 hrs) FC	Not Exp.	136.0	127.1	16.0*
			"	"	138.5	128.0	21.0
			"	0.10	139.7	124.5	5.0(4)

(continued)

(Table 11 - continued)

Gage, in.	Sheet No.	Rolling Temp, F	Annealing Treatment	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong(1"), %
			1450F (2 hrs) AC	Not Exp.	142.7	136.2	19.0
			"	0.15	139.5	130.2	3.0(2)
			"	0.21	143.5	130.3	6.0(1, 2, 3)
			1550 (1 hr) AC	Not Exp.	137.8	125.0	18.0
			"	0.13	143.7	134.2	20.0 (6)
			"	0.075	139.2	126.3	7.0(1)
(22 ppm H_2)			1650F (1/2 hr) AC	Not Exp.	135.9	123.3	19.0
			"	0.067	136.7	122.4	8.0
			"	0.044	139.1	127.8	17.0 (6)
(35 ppm H_2)			1650F (2 hrs) AC	Not Exp.	131.1	118.6	19.0
			"	0.006	134.5	124.2	7.0
			"	0.030	136.5	124.4	13.0 (6)
(27 ppm H_2)			1750F (1/2 hr) AC	Not Exp.	134.0	121.7	19.0
			"	0.059	135.1	125.5	5.0 (4)
			"	0.033	137.1	124.8	18.0 (6)
0.020 (0.089% O_2, 57 ppm H_2)	A-4811	1800	1450F (2 hrs) AC	Not Exp.	144.8	132.1	14.0
			"	0.17	129.6	123.6	3.0 (2, 3)
			"	0.19	92.4	(5)	0 (2, 3)
			1550F (1 hr) AC	Not Exp.	139.3	129.7	12
			"	0.13	137.2	131.0	3 (2, 3)
			"	0.16	136.0	127.2	4 (4)
			1650F (1/2 hr) AC	Not Exp.	142.7	129.5	13.5
			"	0.057	132.4	126.1	2.0
			"	0.064	120.7	(5)	0 (3)
			1650F (2 hrs) AC	Not Exp.	132.7	125.9	12 (1)
			"	0.032	130.0	123.5	2 (1, 4)
			"	0.050	119.3	(5)	0 (2)
			1750F (1/2 hr) AC	Not Exp.	131.8	120.9	14
			"	0.083	136.2	128.1	11
			"	0.11	119.3	(5)	0 (4)

(continued)

(Table 11 continued)

Gage, in	Sheet No.	Rolling Temp, F	Annealing Treatment	Creep Def, %	UTS Ksi	YS(0.2%), Ksi	Elong (1"), %
0.062	A-4799	1800	1450F (2 hrs) AC	Not Exp.	143.4	131.6	19.0
(0.086% O_2,			"	0.18	144.0	133.9	12.0(4)
40-55 ppm H_2)			"	0.19	142.8	132.0	7 (4)
			1550F (1 hr) AC	Not Exp.	142.7	130.0	19.0
			"	0.097	142.2	131.0	19.0(6)
			"	0.14	141.2	130.0	7.0(4)
(52 ppm H_2)			1650F (1/2 hr) AC	Not Exp.	136.1	126.4	8.0(1)
			"	0.073	139.6	129.3	7.0
			"	0.062	139.0	127.4	9.0(6)
(44 ppm H_2)			1650F (2 hrs) AC	Not Exp.	136.0	123.9	24.0
			"	0.028	138.2	125.2	17.0
			"	0.031	128.2	125.5	0 (4)
			1750F (1/2 hr) AC	Not Exp.	138.2	125.7	22.5
			"	0.076	138.8	130.6	11.0(4)
			"	0.093	136.5	129.0	4.0
0.090	A-4808	1800	1450F (2 hrs) AC	Not Exp.	139.0	129.7	20.0
(0.073% O_2,			"	0.15	137.5	131.3	4.0(4)
23-37 ppm H_2)			"	0.17	142.0	131.9	21.0(6)
			1550F (1 hr) AC	Not Exp.	138.1	127.3	20.0
			"	0.13	140.6	129.4	19.0
			"	0.10	129.3	128.8	1.0(4)
(39 ppm H_2)			1650F (1/2 hr) AC	Not Exp.	137.5	124.2	21.0
			"	0.074	137.4	130.4	7.0
			"	0.065	134.6	128.0	3.0(1, 4)
(33 ppm H_2)			1650F (2 hrs) AC	Not Exp.	133.1	121.9	23.0
			"	0.070	136.7	125.4	18.0
			"	0.036	114.6	(5)	0 (3)

(concluded)

(Table 11 concluded)

Gage, in	Sheet No.	Rolling Temp, F	Annealing Treatment	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong(1"), %
			1750F (1/2 hr) AC	Not Exp.	135.0	121.8	21.5
			"	0.10	136.6	128.8	19.0(6)
			"	0.064	134.7	127.2	5.0

(*) 2in gage length specimens; all others 1 in gage length.

(1) Broke at end of gage length.

(2) Evidence of severe stress corrosion in fracture.

(3) Tensile tested after acid pickling 0.002" from gage of creep-exposed specimens; stress corrosion evident in fracture.

(4) Evidence of slight-to-moderate stress corrosion.

(5) Broke before yield stress.

(6) Tensile tested after acid pickling 0.002" from gage of creep exposed specimen.

TABLE 12 THERMAL- AND CREEP- STABILITY PROPERTIES OF Ti-7Al-12Zr SHEETS FINISH ROLLED FROM 1750F (Originally mill annealed 1350F for 8 hrs and laboratory annealed as indicated; longitudinal specimens from V-1541)

Gage, in	Sheet No.	Annealing Cycle	Stability Exposure	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong(1"), %
0.020	A-4798	1650F (1 hr) AC	Not Exp	-	136.4	120.1	18
(0.109% O_2,			1000F - 150 hrs	-	138.8	127.0	13.5
78-90 ppm H_2)			1000F - 25 Ksi - 150 hrs	0.044	Broke before YS		0 (1, 2)
			"	0.041	137.3	127.5	7
		1650F (4 hrs) AC	Not Exp	-	131.2	120.4	18
			1000F - 150 hrs	-	131.8	122.3	6
			1000F - 25 Ksi - 150 hrs	0.028	123.5	109.4	9 (1)
			"	0.019	131.8	120.9	3
		1650F (1/2 hr) AC + 1300F (8 hrs)	Not Exp	-	137.0	127.2	18
			1000F - 150 hrs	-	138.8	130.4	13
			1000F - 25 Ksi - 150 hrs	0.070	Broke before YS		0 (3)
			"	0.075	134.4	120.5	17 (1)
		1750F (1/2 hr) AC + 1300F (8 hrs)	Not Exp	-	137.6	132.2	17.5
			1000F - 150 hrs	-	140.7	131.9	13
			1000F - 25 Ksi - 150 hrs	0.16	140.0	130.9	14
			"	0.13	131.5	118.4	3 (1, 3)
		1650F (1/2 hr) AC + 1750F (5 min) AC	Not Exp	-	144.0	130.1	13
			1000F - 150 hrs	-	140.0	132.0	14.5
			1000F - 25 Ksi - 150 hrs	0.059	131.4	129.6	1.0
			"	0.056	126.0	106.2 (4)	4 (1)

(continued)

(Table 12 - continued)

Gage, in.	Sheet No.	Annealing Cycle	Stability Exposure	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong (1"), %
0.062	A-4802	1650F (1 hr) AC	Not Exp	-	128.3	121.6	19
(0.091% O_2,			1000F - 150 hrs	-	131.9	120.7	20.5
35-41 ppm H_2)			1000F - 25 Ksi - 150 hrs	0.012	130.4	119.5	17
			"	0.012	131.7	121.8	17
		1650F (4 hrs) AC	Not Exp	-	127.9	119.0	19
			1000F - 150 hrs	-	131.1	118.6	17
			1000F - 25 Ksi - 150 hrs	0.009	128.5	115.5	20 (1)
			"	0.012	131.2	119.1	11 (2)
		1650F (1/2 hr) AC + 1300F (8 hrs)	Not Exp	-	130.1	124.2	21
			1000F - 150 hrs	-	134.1	123.6	20
			1000F - 25 Ksi - 150 hrs	0.082	131.7	120.5	17
			"	0.084	131.5	120.8	17.5
		1750F (1/2 hr) AC + 1300F (8 hrs)	Not Exp	-	136.9	129.4	19
			1000F 150 hrs	-	136.3	126.8	20.5
			1000F - 25 Ksi - 150 hrs	0.106	135.5	125.0	19
			"	0.113	135.4	124.2	10
		1650F (1/2 hr) AC + 1750F (5 min) AC	Not Exp	-	134.0	119.6	21
			1000F - 150 hrs	-	133.4	124.4	18
			1000F - 25 Ksi - 150 hrs	0.016	131.1	120.7	18
			"	0.028	133.4	121.4	18

(continued)

(Table 12 - concluded)

Gage, in.	Sheet No.	Annealing Cycle	Stability Exposure	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong(1"), %
0.090 (0.073% O_2, 32-40 ppm H_2)	A-4809	1650F (1 hr) AC	Not Exp.	-	132.6	118.7	22
			1000F - 150 hrs	-	138.9	127.4	13
			1000F - 25 Ksi - 150 hrs	0.022	138.4	125.5	15 (1)
			"	0.019	137.6	126.1	5
		1650F (4 hrs) AC	Not Exp.	-	132.1	113.1	22
			1000F - 150 hrs	-	136.7	124.9	7.5
			1000F - 25 Ksi - 150 hrs	0.000	135.8	122.7	12.5 (1)
			"	0.022	134.9	123.3	3 (2)
		1650F (1/2 hr) AC + 1300F (8 hrs)	Not Exp.	-	134.2	120.6	22
			1000F - 150 hrs	-	139.9	129.0	14
			1000F - 25 Ksi - 150 hrs	0.101	138.0	126.6	10 (2)
			"	0.086	138.9	127.4	18.5 (1)
		1750F (1/2 hr) AC + 1300F (8 hrs)	Not Exp.	-	136.4	125.9	23
			1000F - 150 hrs	-	142.1	131.6	15
			1000F - 25 Ksi - 150 hrs	0.116	139.7	128.3	19 (1)
			"	0.128	138.8	129.0	5
		1650F (1/2 hr) AC + 1750F (5 min) AC	Not Exp.	-	136.0	119.8	22
			1000F - 150 hrs	-	139.5	128.0	14
			1000F - 25 Ksi - 150 hrs	0.019	134.7	127.9	1 (5)
			"	0.043	130.4	125.3	2 (1, 3)

(1) Tensile tested after acid pickling 0.003" from gage of creep-exposed specimen; all others tensile tested without any surface conditioning.
(2) Rough cracked surface adjacent to fracture.
(3) Evidence of stress corrosion in fracture.
(4) Erroneous value due to slight misalignment of specimen in file grips.
(5) Broke at end of gage length.

In contrast to the consistently good stability obtained in Ti-5Al-5Sn -5Zr, the question of the stability of Ti-7Al-12Zr sheet is quite evident from the results of Tables 11 and 12. Just as in the creep-stability tests described in the Ninth Bimonthly Report[3], a very substantial number of specimens suffered incidental stress corrosion damage, thus masking the true stability evaluation of the three sheets. The fact that this is the second large group of Ti-7Al-12Zr samples which has been so adversely affected by stress corrosion, while Ti-5Al-5Sn-5Zr samples tested at the same time were relatively free of such damage, lends further support to the prior postulation that Ti-7Al-12Zr is far more sensitive to incidental stress corrosion at 1000F than Ti-5Al-5Sn-5Zr[3].

Considering the 1000F creep resistance shown in Tables 11 and 12, it is seen that, just as with Ti-5Al-5Sn-5Zr (Table 10), the creep deformation of Ti-7Al-12Zr decreased with increased simulated mill annealing temperature (1400-1500F). Furnace cooling generally produced somewhat inferior creep resistance compared to corresponding air cooled samples. The best creep properties were afforded by simple annealing at 1650F with a one-hour cycle providing lower deformation values than the 30 minute treatment. However, except for the 0.020in sheet finish rolled from 1750F, extending the annealing time to 2-4 hours produced little or no improvement in creep resistance at 1000F - 25 Ksi compared to the one-hour cycle. Simple annealing at 1750F (1/2 hr) AC compared to 1650F (1/2 hr) AC resulted in about the same or perhaps slightly greater deformation values, although compared to 1650F (2 to 4 hrs) AC, the creep resistance was substantially inferior after annealing at 1750F (1/2 hr) AC. Superimposing a cycle of 1350F (8 hrs) on the simple annealing treatments of 1650F and 1750F (see Table 12) provided somewhat greater creep deformation, compared to the respective simple annealing treatments, especially at 1750F. Flash annealing at 1750F (5 min) AC in the alpha-beta field after having annealed at 1650F (1/2 hr) AC resulted in somewhat better creep properties than were achieved

by the simple cycle of 1650F (1/2 hr) AC, although the deformation values were greater than after simple annealing at 1650F (1 hr) AC.

Based on the data discussed above, finish annealing of Ti-7Al-12Zr sheet at 1650F offers the best 1000F creep resistance, particularly with cycles of one hour or longer. However, the problem of oxidation and contamination during long-time annealing in air must be considered; again, from the standpoint of compromise, 1650F (1/2 hr) AC appears to be a reasonable choice to obtain good creep resistance in Ti-7Al-12Zr sheet. An alternative would be longer-time annealing in the absence of air, and this might entail slow cooling (such as vacuum annealing) which would definitely lower the creep resistance.

Of the Ti-7Al-12Zr stability results listed in Tables 11 and 12 which were not affected by incidental stress corrosion, the sheets finish rolled from 1750F generally exhibited somewhat better stability than those rolled from 1800F. The 0.062in sheet rolled from 1750F (Tables 11 and 12) possessed the best stability by far; reasons for this are not known, since this sheet analyzed 0.09 percent O_2 compared to the 0.090in sheet containing 0.073in percent oxygen. Other factors being equal, one would expect better stability from the lower oxygen material. All of the specimens in Tables 10-12 were cut from mill annealed, ground, and pickled sheets and were laboratory annealed with no further pickling. Also, specimens which were annealed for times of one hour or longer were sealed between air-tight covers of commercially pure titanium to eliminate oxidation; these were then pickled after annealing. Therefore, residual contamination should not have been a factor in the stability tests. However, in some instances, there may possibly have been a minute amount of surface contamination remaining which could have affected a few of the results.

From the data presented in Table 12 it is seen that a thermal exposure at 1000F without stress was a good indicator of

stability; i. e., the subsequent tensile elongation after such unstressed storage was often intermediate between the original ductility and the elongation obtained on specimens exposed to 1000F under stress of 25 Ksi. However, considering only the creep-stability results, it appears that as good a level of stability was achieved after annealing at 1650F as any other temperature and, of course, this treatment temperature provides the best creep resistance, also. In a few instances, reasonably good stability was also observed by alpha-beta annealing at 1750F, but the data are so scattered that no firm conclusions can be made regading its value for improving stability. In the 0.062in sheet rolled from 1750F, the as-exposed elongation was higher after annealing for 1 and 2 hours at 1650F than for 0.5 and 4 hours (17-20% versus 11%). However, this was not true for the 0.020 and 0.090in sheets in which the elongation after creep exposure was nearly as high for the 0.5 hour cycle as for the longer annealing times at 1650F. In the 0.062 and 0.090in sheets rolled from 1800F the as-exposed elongation level was greater for the 2 hour treatment than the 0.5 hour cycle at 1650F.

Based on the results discussed above, it appears that some additional benefit in stability might be achieved in some sheets of Ti-7Al-12Zr by extending the annealing time beyond 30 minutes. However, this improvement, if any, was not at all consistent. Such benefits in stability and creep properties are, of necessity, offset by the problem of oxidation which would be encountered during longer annealing times of one to two hours in air. Such excessive contamination, particularly in thin gage sheets, might even aggravate the stability problem in Ti-7Al-12Zr. As alternatives, protective coatings or inert atmosphere heating (vacuum or inert gas) could be used, but these can be cumbersome operations which would require considerable development work before they could be considered routine procedures. Also, as mentioned earlier in this section, the possibility of slow cooling exists if vacuum or inert gas annealing were used and this would lower the creep resistance substantially.

Considering the various factors involved, 1650F (1/2 hr) AC was selected as an optimum finish annealing cycle for Ti-7Al-12Zr sheet, realizing that it possesses both advantages and disadvantages in the overall picture of production operations and mechanical properties. This treatment will be used on all Ti-7Al-12Zr sheets produced in the contract.

Properties of Welded Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheet

One 0.062in sheet of each of the two alloys was fusion welded without filler (TIG welded) using procedures and conditions quite similar to those previously utilized on Ti-8Al-1Mo-1V[5]. Welded panels were then evaluated on the basis of as-welded and welded-and-annealed tensile and bend, sub-zero temperature notch tensile, and creep-stability properties. Originally, this investigation was proposed for the two initial 0.062in sheets which had been finish rolled from 1750F. However, because of a shortage of material, the sheet of 0.062in Ti-5Al-5Sn-5Zr finish rolled from 1800F was used since it possessed good properties and, in addition, it was felt that in an evaluation of the weld metal itself the contribution by the parent metal would be small. Therefore, since the 1800F rolled sheet of Ti-5Al-5Sn-5Zr was of good quality, it was used in the study without reservations. However, the 0.062in sheet of Ti-7Al-12Zr was finish rolled from 1750F.

Both sheets were welded in the mill annealed condition (1350F for 8 hrs) and tested as welded and after post weld annealing at 1100F (1 hr) AC and 1650F (1/2 hr) AC. Results of tensile and bend tests are listed in Tables 13 and 14. Elongation values in transverse samples were measured in 0.5in gage length which encompassed nearly 100 percent weld metal, a technique used previously for Ti-8Al-1Mo-1V[5]. As the results in Tables 13 and 14 show, both alloys possessed good strength and ductility as welded and as welded-and-annealed at 1650F (1/2 hr) AC. As measured by the transverse specimen, which is more an indication of true weld properties, the elongation and bendability improved markedly by annealing at 1650F (1/2 hr) AC. On the other hand, stress relieving at 1100F (1 hr) AC changed the weld bendability of Ti-5Al-5Sn-5Zr little, if any, but increased the longitudinal weld bend radius of Ti-7Al-12Zr from 4.2 to 7.6T. The 1100F treatment also increased the transverse strength of welded Ti-7Al-12Zr 4-5 Ksi while the transverse strength of Ti-5Al-5Sn-5Zr was unaffected. These findings indicate that some hardening reaction is operative at 1100F. Strengths of Ti-7Al-12Zr at all testing temperatures were higher than those of Ti-5Al-5Sn-5Zr, an observation made earlier on the parent material[3].

TABLE 13 ROOM- AND ELEVATED- TEMPERATURE TENSILE PROPERTIES OF 0.062in WELDED Ti-5Al-5Sn-5Zr SHEET WITH AND WITHOUT POST WELD ANNEALING (V-1540, Sheet A-4804 finish rolled from 1800F, mill annealed 1350F - 8 hrs, and welded)

Condition	Test Temp, F	Dir Weld to Test	UTS, Ksi	YS(0.2%), Ksi	El (1/2"), %	El (1"), %	El (2"), %	MBR, T
Parent Metal (Mill Annealed)	RT	L	128.7	122.8	-		18.3	3.6
As Welded	RT	L	138.2	116.9	-		8.0	5.0
Weld + 1100F (1 hr) AC	RT	L	141.2	128.4	-		8.0	4.1
Weld + 1650F (1/2 hr) AC	RT	L	126.9	113.9	-		9.0	3.0
As Welded	RT	T	137.1*	125.2	8.0		-	4.9
Weld + 1100F (1 hr) AC	RT	T	137.1*	126.7	4.0		-	5.0
Weld + 1650F (1/2 hr) AC	RT	T	130.6*	120.9	15.0		-	-
As Welded	800	L	105.1	81.2	-	9.5	-	
Weld + 1100F (1 hr) AC	800	L	107.0	86.0	-	10.0	-	
Weld + 1650F (1/2 hr) AC	800	L	88.7	67.2	-	16.5	-	
As Welded	1000	L	102.0	76.7	-	9.5	-	
Weld + 1100F (1 hr) AC	1000	L	102.4	78.3	-	8.0	-	
Weld + 1650F (1/2 hr) AC	1000	L	83.7	64.7	-	12.5	-	

(*) Specimens broke in heat affected zone outside of weld.

TABLE 14 ROOM- AND ELEVATED- TEMPERATURE TENSILE PROPERTIES OF 0.062in WELDED Ti-7Al-12Zr SHEET WITH AND WITHOUT POST-WELD ANNEALING (V-1541, Sheet A-4802 finish rolled from 1750F, mill annealed 1350F - 8 hrs, and welded).

Condition	Test Temp, F	Dir Weld to Test	UTS, Ksi	YS(0.2%), Ksi	El (1/2"), %	El (1"), %	El (2"), %	MBR, T
Parent Metal (Mill Annealed)	RT	L	149.7	143.7	-		13.8	4.4
As Welded	RT	L	152.5	129.4	-		7.0	4.2
Weld + 1100F (1 hr) AC	RT	L	143.7	137.9	-		2.0	7.6
Weld + 1650F (1/2 hr) AC	RT	L	130.7	118.9	-		6.0	<4.5
As Welded	RT	T	156.7*	144.3	12.0		-	4.0
Weld + 1100F (1 hr) AC	RT	T	161.3*	148.6	15.5		-	4.8
Weld + 1650F (1/2 hr) AC	RT	T	142.7*	133.2	17.5		-	< 2.9
As Welded	800	L	121.8	98.7	-	11.0	-	
Weld + 1100F (1 hr) AC	800	L	122.3	98.9	-	6.0	-	
Weld + 1650F (1/2 hr) AC	800	L	97.9	77.5	-	12.0	-	
As Welded	1000	L	119.5	85.6	-	10.5	-	
Weld + 1100F (1 hr) AC	1000	L	118.7	90.8	-	10.0	-	
Weld + 1650F (1/2 hr) AC	1000	L	92.3	70.8	-	14.0	-	

(*) Specimens broke in heat-affected zone outside of weld

Notch and standard tensile properties of welded sheet at sub-zero temperatures are illustrated in Figures 3 through 8 for Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr. Tensile elongation of welded Ti-5Al-5Sn-5Zr did not suffer appreciably as the temperature was lowered to -320F, but the ductility of welded Ti-7Al-12Zr dropped to very low levels at -110 and -320F. In the latter alloy, stress relieving at 1100F (1 hr) improved the low temperature ductility some (Figure 7), but not nearly as much as annealing at 1650F (1/2 hr) AC. In all three conditions the notch strength of both alloys at K_t=3 was greater than the unnotched down to -320F but at K_t=6, a much sharper notch, the as-welded notch strength fell below the unnotched at about -200 and -250F for Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr, respectively. After annealing the welds at 1650F (1/2 hr) AC, these two temperatures (where the notch strength ratio at K_t=6 drops below 1.0) were approximately -270 and -230F, respectively. Thus, it is seen that both alloys possessed good sub-zero temperature notch tensile properties as-welded and as welded-and-annealed at 1650F (1/2 hr) AC. However, a postweld stress relieving cycle of 1100F (1 hr) AC produced decidedly inferior notch properties (K_t=6) at temperatures only slightly below ambient (see Figures 4 and 7), again indicating that some hardening or embrittling reaction is occurring at 1100F.

Results of creep-stability tests on the two welded sheets are presented in Table 15 and show that welded Ti-5Al-5Sn-5Zr exhibits much better stability than Ti-7Al-12Zr. However, both alloys appear to lose more elongation after creep exposure at 1000F than at 800F. Some of the instability displayed by Ti-7Al-12Zr resulted from a surface reaction, since acid pickling after exposure improved the tensile elongation. None of the duplicate Ti-5Al-5Sn-5Zr specimens was acid pickled, since tensile testing the first of each set of two indicated no serious loss in ductility. The creep deformation data are of particular interest; in both alloys postweld annealing at 1650F (1/2 hr) AC substantially improved the 1000F creep resistance and, to a lesser extent, at 800F also. However, the postweld stress relieving treatment of 1100F (1 hr) AC had little or no effect on the weld creep properties.

Photomicrographs of the fusion and heat-affected zones are depicted in Figures 9 through 17. The first four (Figures 9-12) are of Ti-

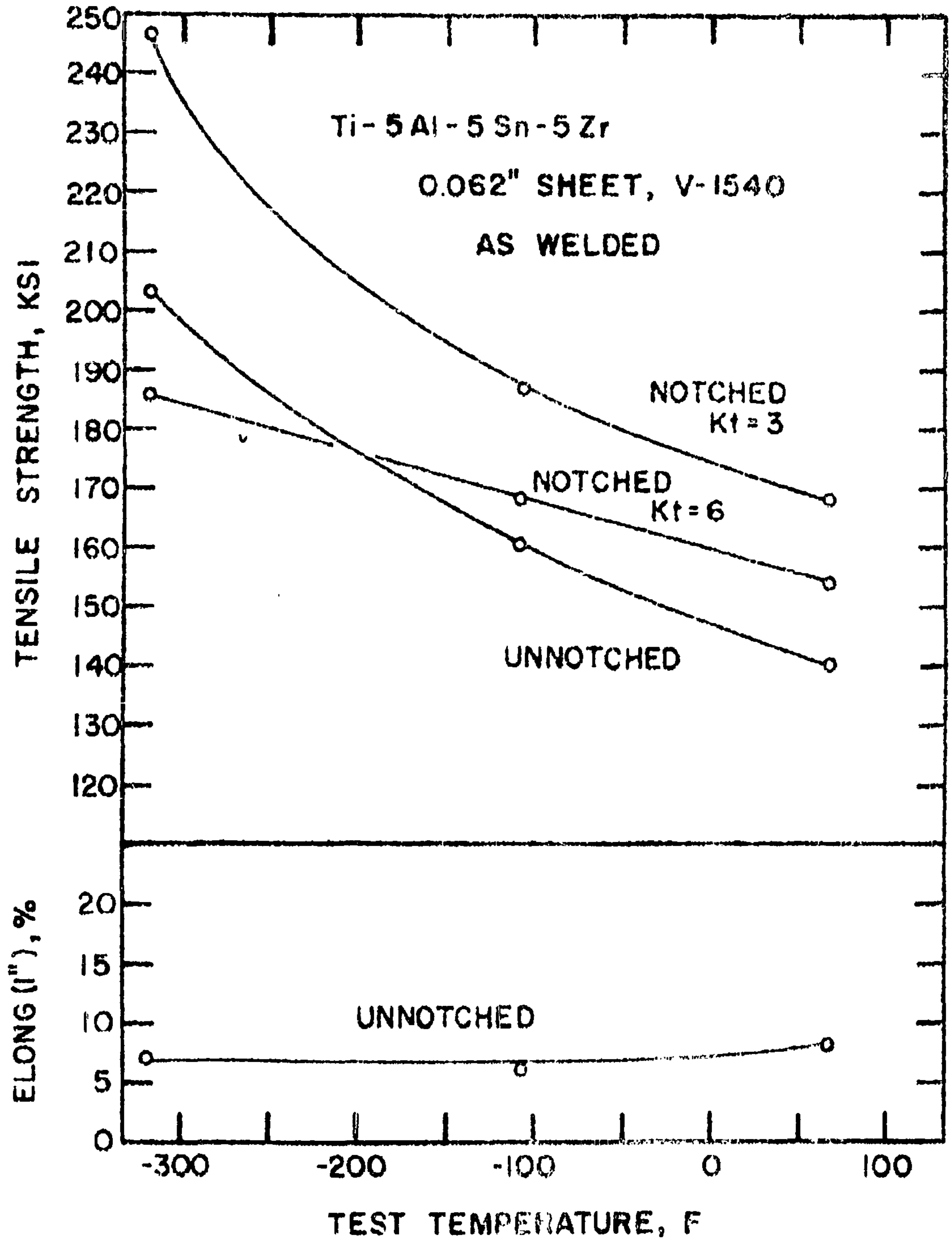


FIGURE 3 SUB-ZERO TEMPERATURE STANDARD AND NOTCH TENSILE PROPERTIES OF AS-WELDED Ti-5Al-5Sn-5Zr SHEET. (V-1540, Sheet A-4804, 0.062in)

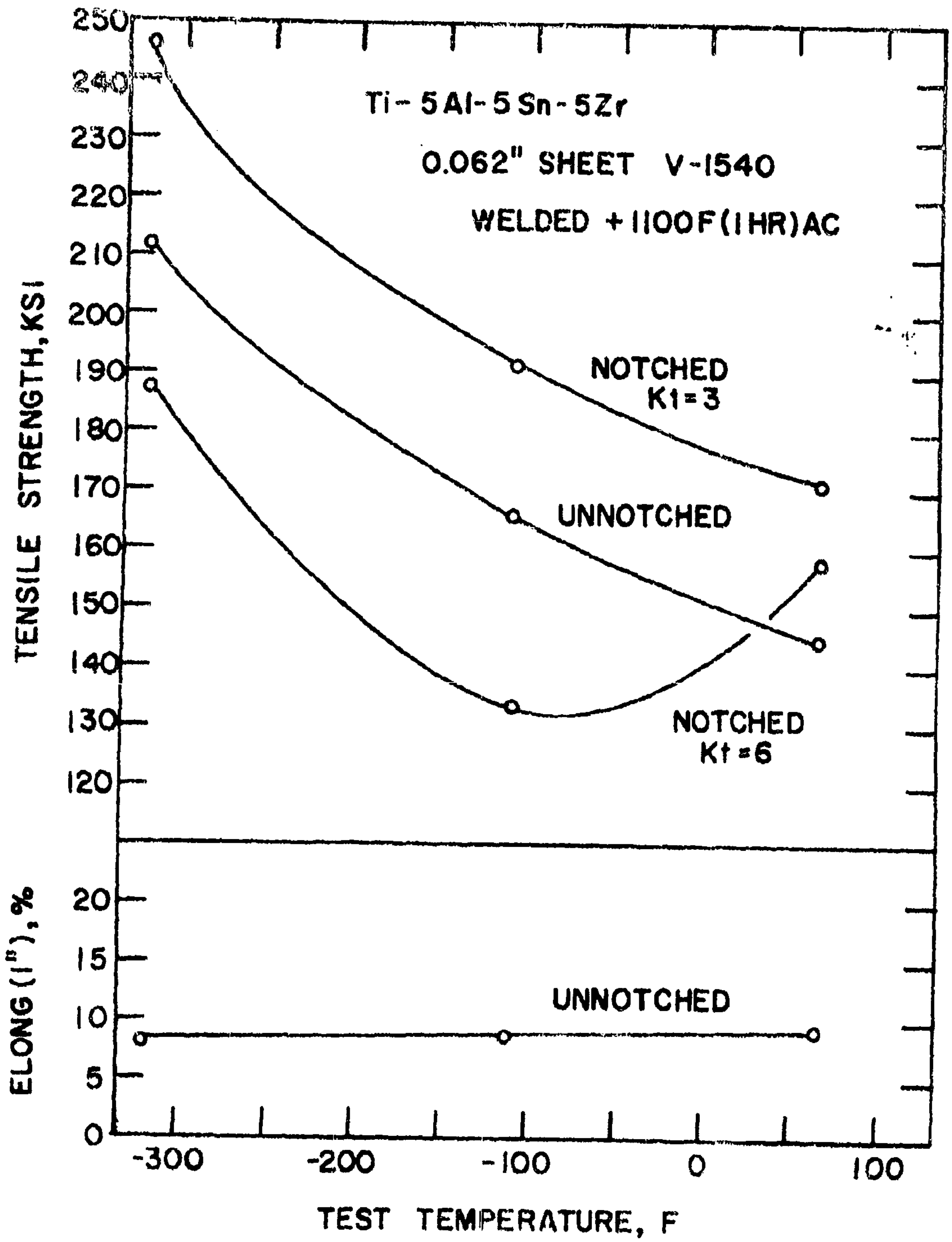


FIGURE 4 SUB-ZERO TEMPERATURE STANDARD AND NOTCH TENSILE PROPERTIES OF WELDED Ti-5Al-5Sn-5Zr SHEET, WELDED + 1100F (1 hr) AC, (V-1540, Sheet A-4804, 0.062in)

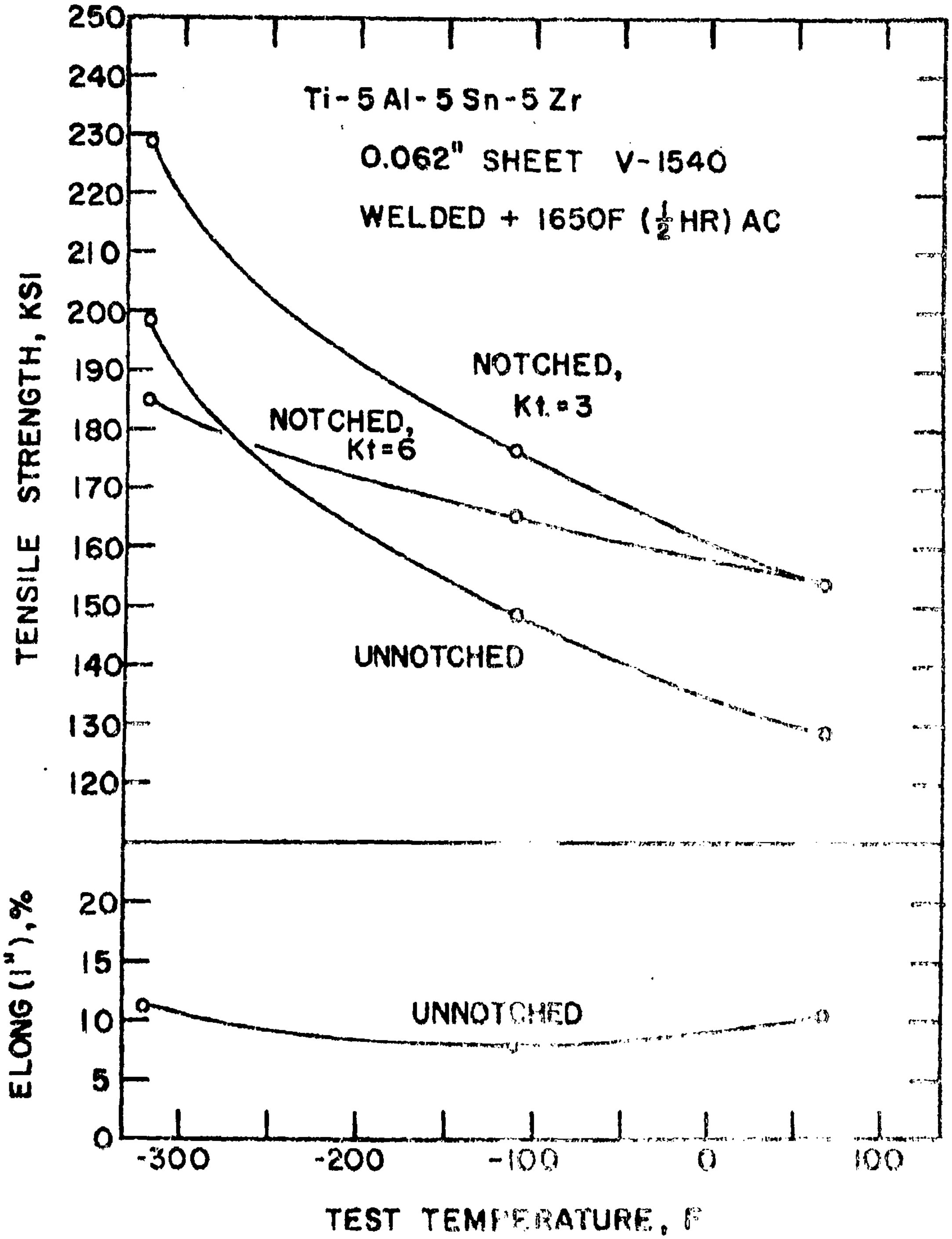


FIGURE 5 SUB-ZERO TEMPERATURE STANDARD AND NOTCH TENSILE PROPERTIES OF WELDED Ti-5Al-5Sn-5Zr SHEET, WELDED + 1650F (1/2 hr) AC (V-1540, Sheet A-4804, 0.062in)

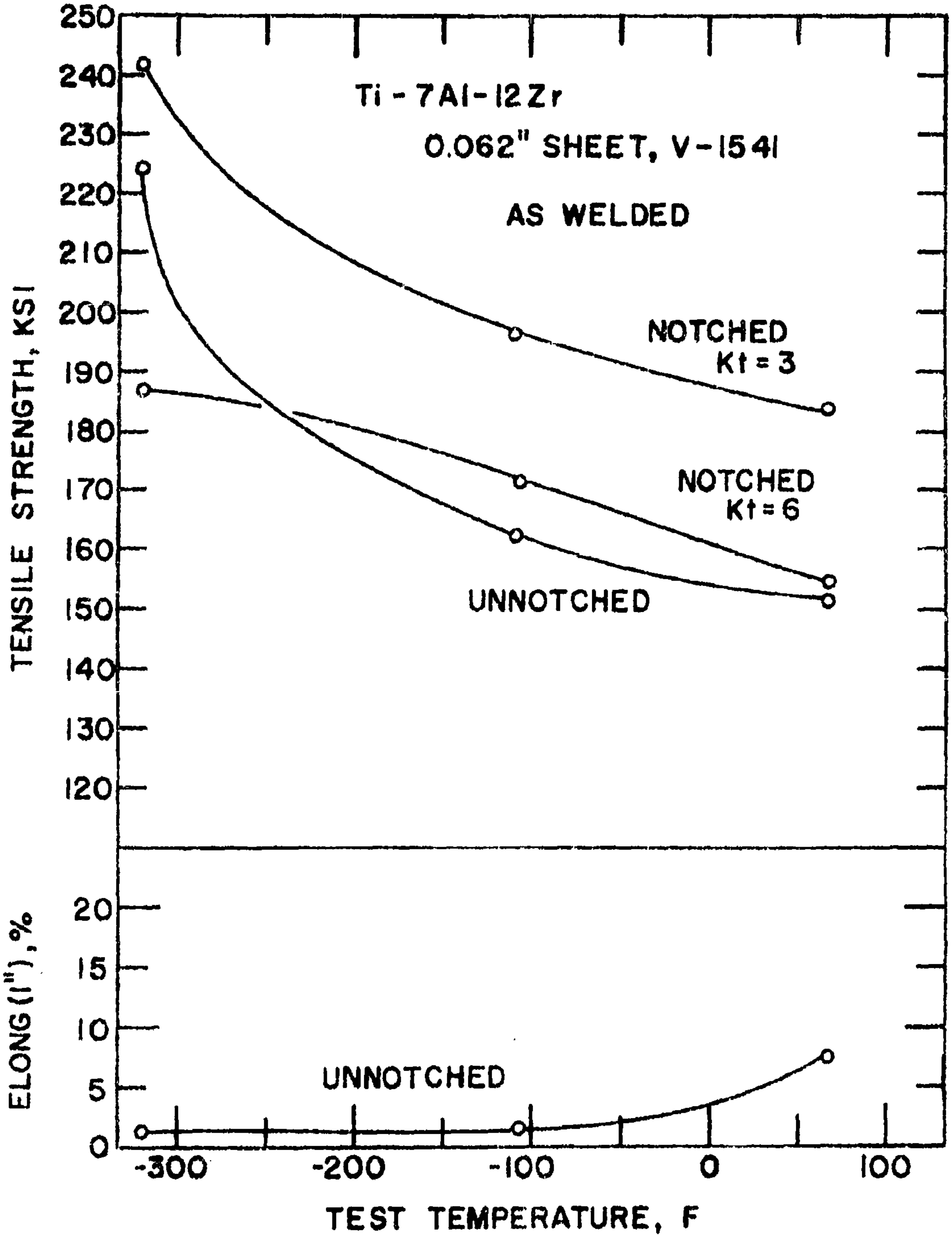


FIGURE 6 SUB-ZERO TEMPERATURE STANDARD AND NOTCH TENSILE PROPERTIES OF AS-WELDED Ti-7Al-12Zr SHEET. (V-1541, Sheet A-4802, 0.062 in.)

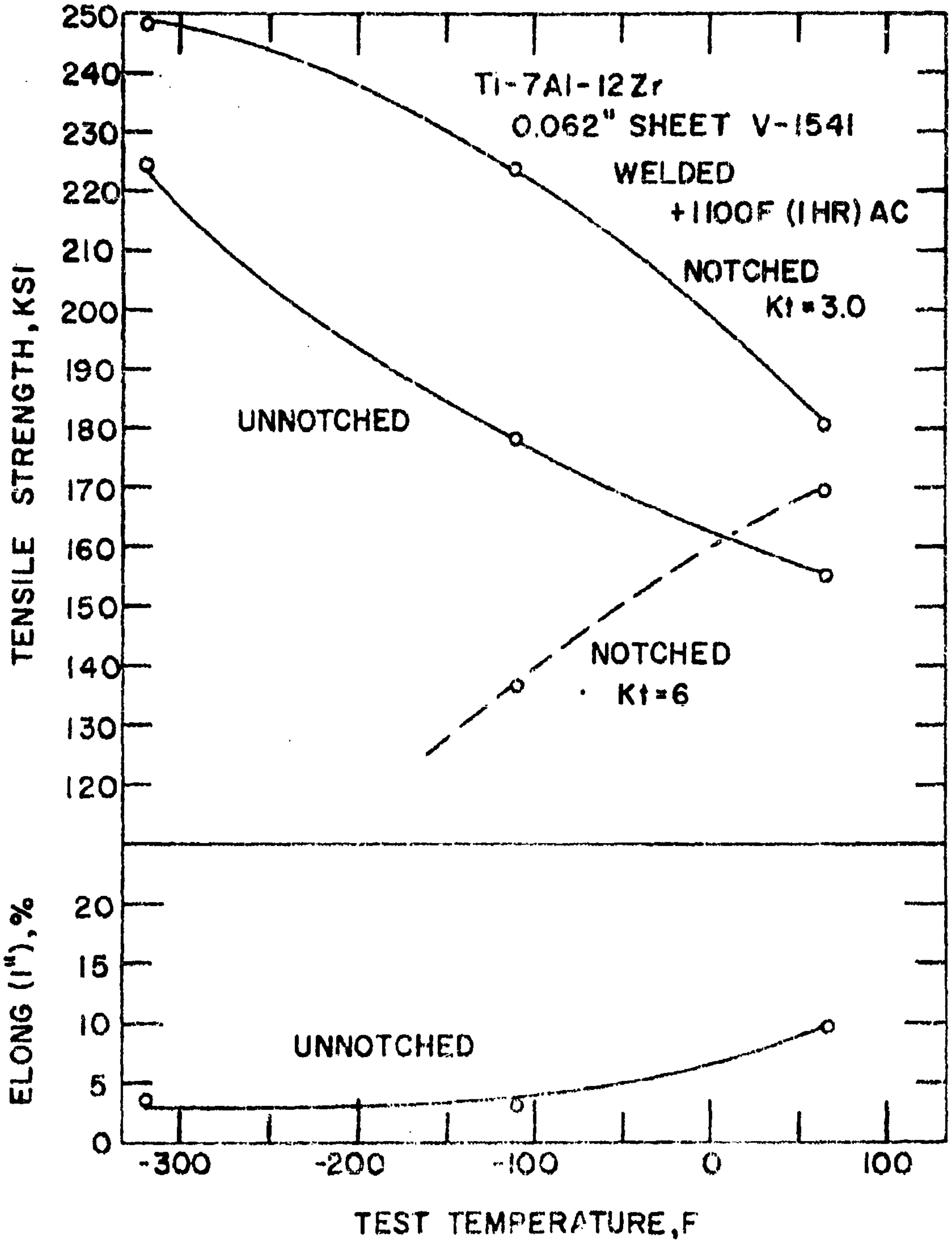


FIGURE 7 SUB-ZERO TEMPERATURE STANDARD AND NOTCH TENSILE PROPERTIES OF WELDED Ti-7Al-12Zr SHEET, WELDED + 1100F (1 hr) AC. (V-1541, Sheet A-4802, 0.062in)

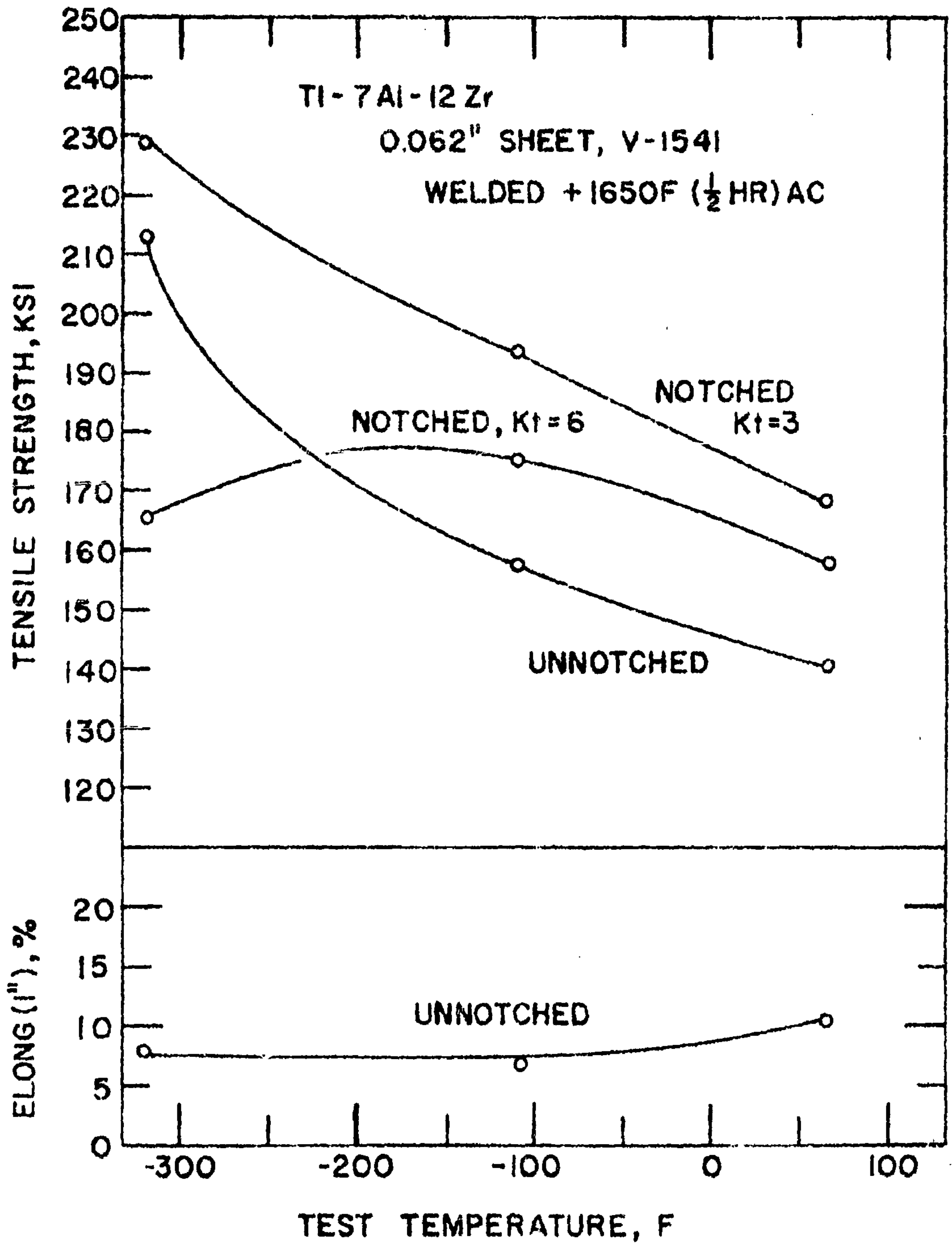
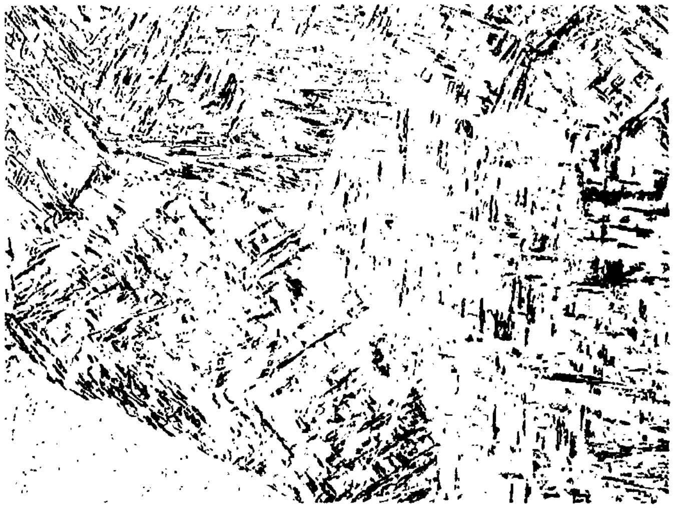


FIGURE 8 SUB-ZERO TEMPERATURE STANDARD AND NOTCH TENSILE PROPERTIES OF WELDED Ti-7Al-12Zr SHEET, WELDED + 1650F (1/2 hr) AC. (V-1541, Sheet A-4802, 0.062 in.)

TABLE 15 CREEP-STABILITY PROPERTIES OF WELDED 0.062in Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr SHEET (Longitudinal Weldments, duplicate specimens tensile tested without surface conditioning after exposure unless noted otherwise)

Condition	Exposure	Creep Def, %	UTS, Ksi	YS(0.2%), Ksi	Elong (1"), %
Ti-5Al-5Sn-5Zr (V-1540, A-4804, 0.062in) -					
As Welded	none	-	140.8	118.3	8.0
1100F (1 hr) AC	"	-	145.2(1)	129.4(1)	11.0(1)
1650F (1/2 hr) AC	"	-	128.9	115.5	11.0
As Welded	800F - 65 Ksi - 150 hrs	.08	141.3	127.3	8.5
1100F (1 hr) AC	"	.10	142.6	129.9	7.0
1650F (1/2 hr) AC	"	.07	133.2	126.5	9.0
As Welded	1000F - 25 Ksi - 150 hrs	.20	137.4	126.4	6.5
1100F (1 hr) AC	"	.21	141.9	129.2	7.0
1650F (1/2 hr) AC	"	.07	131.4	120.9	6.0
Ti-7Al-12Zr (V-1541, A-4802, 0.062") -					
As Welded	none	-	152.0	128.8	7.5
1100F (1 hr) AC	"	-	155.5	138.4	9.5
1650F (1/2 hr) AC	"	-	140.7	126.3	11.0
As Welded	800F - 65 Ksi - 150 hrs	.07	151.0	136.0	7.0
"	"	.06	160.5	144.8	8.0(2)
1100F (1 hr) AC	"	.05	157.0	144.0	4.0
"	"	.06	162.9	149.7	7.0(2)
1650F (1/2 hr) AC	"	.03	145.0	131.0	8.0
"	"	.02	142.4	134.6	11.0(2)
As Welded	1000F - 25 Ksi - 150 hrs	.24	160.0	146.0	3.0
"	"	.33	162.9	148.1	5.0(2)
1100F (1 hr) AC	"	.35	162.0	148.0	3.0
"	"	.27	162.1	149.0	5.5(2)
1650F (1 hr) AC	"	.07	147.0	136.0	3.0
"	"	.02	130.7	124.3	1.5(2)

(1) Results of single specimen. (2) Acid pickled to remove 0.002in from gage after exposure

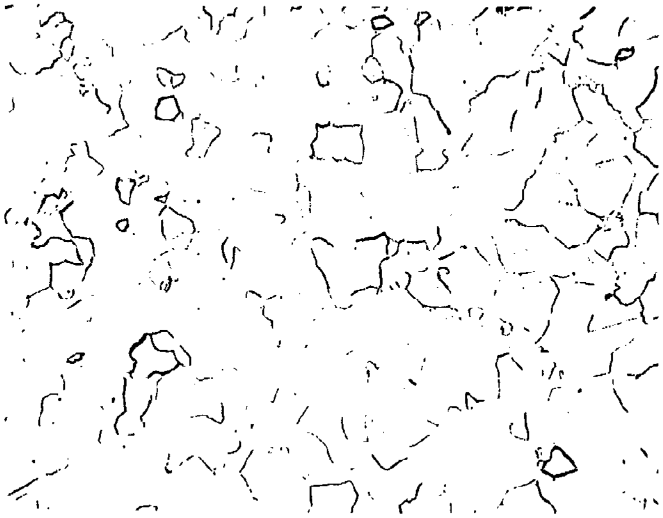


61-72-A3 150X

FIGURE 9 Ti-5Al-5Sn-5Zr, V-1540, 0.062in SHEET. FUSION ZONE AS WELDED.

61-72-A4 150X

FIGURE 10 Ti-5Al-5Sn-5Zr, V-1540, 0.062in SHEET. HEAT-AFFECTED ZONE, AS WELDED, SHOWING TRANSITION FROM PARENT METAL ON LEFT TO HEAT AFFECTED MATERIAL ON RIGHT.

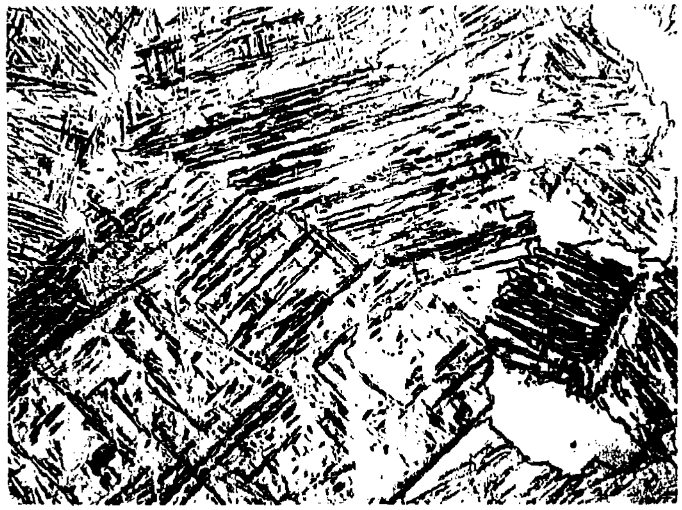


61-72-B4 150X

FIGURE 11 Ti-5Al-5Sn-5Zr, V-1540, 0.062in SHEET. HEAT-AFFECTED ZONE, WELDED + 1650F (1/2 hr) AC, SHOWING RECRYSTALLIZATION OF PARENT METAL AND HEAT-AFFECTED ZONE.

61-72-C4 150X

FIGURE 12 Ti-5Al-5Sn-5Zr, V-1540, 0.062in SHEET, HEAT-AFFECTED ZONE, WELDED + 1100F (1 hr) AC. NOTE APPEARANCE OF MORE PRECIPITATE IN TRANSITION ZONE THAN IS EVIDENT IN FIGURE 10.



61-29-A1 150X

FIGURE 13 Ti-7Al-12Zr, V-1541, 0.062in SHEET. FUSION ZONE, AS WELDED.

61-29-A3 150X

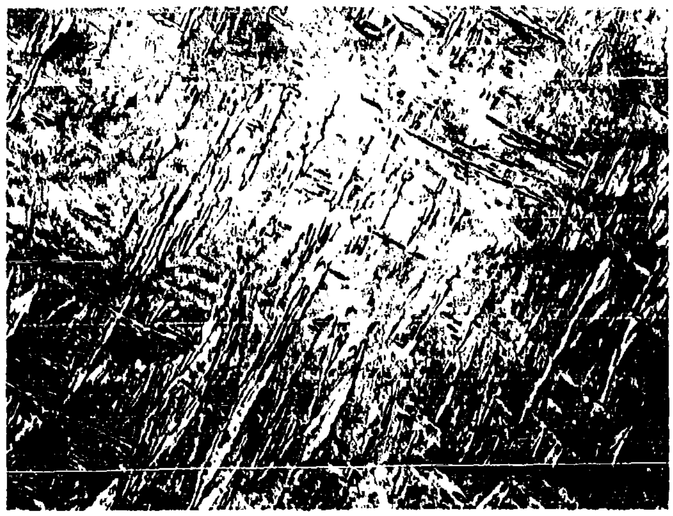
FIGURE 14 Ti-7Al-12Zr, V-1541, 0.062in SHEET. HEAT-AFFECTED ZONE, AS WELDED, TRANSITION ZONE BETWEEN PARENT METAL ON LEFT AND RECRYSTALLIZED MATERIAL ON THE RIGHT.

61-29-C1 150X

FIGURE 15 Ti-7Al-12Zr, V-1540, 0.062in SHEET. FUSION ZONE, WELDED + 1100F (1 hr) AC.

61-29-C2 150X

FIGURE 16 Ti-7Al-12Zr, V-1541, 0.062in SHEET. HEAT-AFFECTED ZONE, WELDED + 1100F (1 hr) AC. TRANSITION ZONE BETWEEN PARENT METAL ON LEFT AND RECRYSTALLIZED MATERIAL ON THE RIGHT.



61-29-B1 150X

FIGURE 17 Ti-7Al-12Zr, V-1541, 0.062in SHEET, FUSION ZONE, WELDED + 1650F (30 min) AC.

5Al-5Sn-5Zr showing the transformed structure of the weld zone (Figure 9), recrystallization of parent and transition metal during postweld annealing at 1650F (1/2 hr) AC (Figure 11), and a comparison of the heat-affected zone before and after 1100F (1 hr) AC (Figures 10 and 12). Of particular interest is the latter comparison, since it appears that the heat-affected zone contains more precipitate after stress relieving at 1100F; at least it has a darker etching characteristic. Figures 13 through 17 illustrate several zones and conditions in welded Ti-7Al-12Zr. As observed in Ti-5Al-5Sn-5Zr, the transition in the heat-affected zone of Ti-7Al-12Zr (Figure 14) presented a darker appearance and different etching behavior. Closer examination at higher magnification revealed that each grain boundary was widened considerably. It is postulated that in this narrow transition zone the material reached a temperature during welding which just exceeded the alph transus and, therefore, beta phase was formed in these grain boundaries. If so, the beta would have been deficient in aluminum and richer in zirconium at temperature and, upon the relatively rapid cooling after welding, this lean-aluminum beta transformed to alpha, thus resulting in transformed grain boundary material which etched differently than the primary alpha grains. Even more important is the fact that these boundaries would also be weaker and this may be the reason why practically all of the transverse tensile specimens tested at room temperature (Tables 13 and 14) broke in the heat-affected zone. Postweld heating at 1100F (1 hr) AC also seemed to promote more precipitate in the structure (Figures 15 and 16), while postweld annealing at 1650F (1/2 hr) AC produced a much cleaner structure in the fusion zone along with some coarsening of the alpha plates into somewhat of a Widmanstatten pattern as shown in Figure 17.

Additional Property Evaluation of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr

As outlined in the Tenth Bimonthly Report [4], a laboratory study is being performed to determine the effect of hydrogen on the tensile and creep-stability properties of both compositions. This investigation is sub-

stantially complete except for hydrogen analyses of several specimens and, therefore, results will be available during the next report period.

Because of the question of surface contamination and its effect on creep-stability, particularly in Ti-7Al-12Zr, studies have been initiated to determine the depth of contamination obtained during hot rolling at 1750F and mill annealing at 1350F (8 hrs) as well as during final annealing at 1650F and to ascertain the effects of such oxidation on bendability and 1000F stability. With this information, it will be possible to determine the amount of surface material to remove prior to final annealing. These data will be obtained during the next period.

Other laboratory evaluation, which has been undertaken, includes measurement of elevated-temperature tensile, sub-zero temperature notch tensile, and 800-1100F creep-stability properties of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets. A somewhat more comprehensive study of stress relieving temperature was also initiated on welded material since the 1100F (1 hr) AC treatment described in the previous section appeared to be detrimental to the weld properties. Except for the latter, these investigations will be completed by the end of the next report period.

PROCESSING OF Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr

With the selection of an optimum finish annealing cycle of 1650F (1/2 hr) AC for both alloys, as described in an earlier section of this report, the sheets from the first two heats, which had previously been finish rolled, mill annealed, and rough ground[3, 4], were finish annealed at 1650F (1/2 hr) AC. However, prior to final annealing a 13in long panel was sheared from one sheet of each gage and composition (a total of six panels) for use in the contamination investigation and additional annealing studies.

During rough surface grinding of the 29 sheets (originally listed in the Ninth Bimonthly Report[3]), serious hot rolling defects were detected on three Ti-7Al-12Zr sheets; therefore, these three pieces

were discarded (two sheets of 0.062in and one sheet of 0.090in). After finish annealing the remaining 26 sheets were finish ground, pickled, and several were tensile and bend tested. Results of these tests will be presented in the Twelfth Bimonthly Report.

In the production phase of the contract, the three 1700-pound ingots of each of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr [4] were pressed to 2-7/8 x 12in slabs, conditioned, and 1-in thick slices cut from the original top, middle, and bottom locations of each heat for chemical analyses. Initial results of the zirconium analyses, particularly in Ti-7Al-12Zr, were quite variable, so much so that a careful review was made of the zirconium analytical procedure and techniques. At the same time, four samples were taken from each 1-in slice for aluminum, zirconium, and tin (where applicable) analyses.

Results of these determinations are listed in Table 16 which show that good uniformity existed throughout each heat. In general, the average aluminum content was very slightly higher in the middle or bottom positions with the zirconium also slightly greater in the middle; however, the latter trend was not consistent. No consistent trend of tin variations was observed. Considering the individual samples within a given 1-in slice, the aluminum and zirconium values were very slightly higher in the interior than at the periphery of the slabs; again, no trend in tin variability was detected. Oxygen levels of the three Ti-5Al-5Sn-5Zr ingots was generally somewhat higher than that of the three heats of Ti-7Al-12Zr even though the same sponge (0.053% O_2) was used for all six ingots. Only one heat of Ti-5Al-5Sn-5Zr (V-1813) contained slightly higher-than-desired oxygen, but not at an unsafe level; reasons for this are not known.

In view of the consistent zirconium values obtained in these six ingots, some question arises regarding the variability previously observed in the first two heats, V-1540 and V-1541, particularly the latter[5]. Because of the improvements in the zirconium analytical technique were recently effected, such that the chemical

TABLE 16 CHEMICAL ANALYSES OF THREE 1700-POUND INGOTS OF EACH OF Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr (Samples taken from 1-in slices of conditioned 2-7/8 x 12in pressed slabs)

Heat No and Position	Sample Location*	Chemical Analyses, % Al	Sn	Zr	Fe	C	N_2	O_2	H_2, ppm
Ti-5Al-5Sn-5Zr									
V-1784 Top	A	4.84	4.67	4.77					
	B	4.91	4.66	4.84					
	C	4.93	4.71	4.69					
	D	4.89	4.73	4.87					
	Av	4.89	4.69	4.79	0.0054	0.012	0.023	0.073	127
V-1784 Mid.	A	4.93	4.75	4.66					
	B	4.94	4.62	4.68					
	C	4.95	4.66	4.72					
	D	4.93	4.69	4.72					
	Av	4.94	4.68	4.70	0.047	0.012	0.032	0.087	124
V-1784 Bot.	A	4.94	4.66	4.69					
	B	4.92	4.65	4.72					
	C	4.94	4.72	4.77					
	D	4.88	4.64	4.56					
	Av.	4.92	4.67	4.69	0.041	0.012	0.022	0.078	110
V-1785 Top	A	4.83	4.81	4.95					
	B	4.93	4.93	4.83					
	C	4.93	4.76	4.80					
	D	4.83	4.85	4.90					
	Av	4.88	4.84	4.87	0.045	0.016	0.022	0.079	154
V-1785 Mid.	A	4.86	4.90	4.93					
	B	4.93	4.87	5.14					
	C	4.98	4.96	4.89					
	D	4.97	4.86	5.09					
	Av.	4.94	4.90	5.01	0.047	0.010	0.032	0.082	154
V-1785 Bot.	A	4.89	4.94	4.83					
	B	4.94	4.96	4.90					
	C	4.91	5.02	4.89					
	D	4.90	5.02	5.09					
	Av	4.91	4.99	4.93	0.046	0.018	0.022	0.076	140
V-1813 Top	A	4.82	4.96	4.81					
	B	4.91	4.95	4.77					
	C	4.87	4.96	4.78					
	D	4.92	4.95	4.92					
	Av.	4.88	4.96	4.82	0.051	0.012	0.027	0.112	127

(cont'd)

(Table 16 - cont'd)

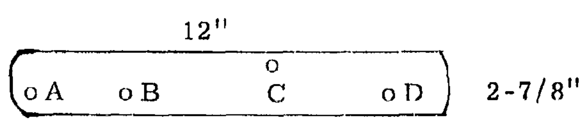
Heat No and Position	Sample Location*	Al	Sn	Zr	Fe	C	N2	O2	H_2, ppm
				Chemical Analyses, %					
(Ti-5Al-5Sn -5Zr)									
V-1813 Mid	A	4.87	4.91	4.78					
	B	4.87	4.98	4.83					
	C	4.89	4.99	4.93					
	D	4.88	4.88	4.99					
	Av.	4.88	4.94	4.88	0.045	0.014	0.020	0.086	162
V-1813 Bot.	A	4.91	4.98	4.77					
	B	4.91	4.93	4.83					
	C	4.91	4.93	4.83					
	D	4.90	4.99	5.03					
	Av.	4.91	4.96	4.87	0.047	0.014	0.022	0.095	170
Ti-7Al-12Zr									
V-1786 Top	A	6.86	-	11.46					
	B	6.85	-	11.55					
	C	6.84	-	11.68					
	D	6.85	-	11.53					
	Av.	6.85	-	11.56	0.048	0.018	0.015	0.066	104
V-1786 Mid.	A	6.88	-	11.50					
	B	6.85	-	11.79					
	C	6.85	-	11.53					
	D	6.86	-	11.40					
	Av.	6.86	-	11.56	0.053	0.012	0.011	0.065	60
V-1786 Bot.	A	6.80	-	11.39					
	B	6.85	-	11.62					
	C	6.86	-	11.43					
	D	6.83	-	11.62					
	Av.	6.84	-	11.52	0.048	0.020	0.016	0.077	54
V-1787 Top	A	6.76	-	11.50					
	B	6.82	-	11.51					
	C	6.83	-	11.53					
	D	6.78	-	11.55					
	Av.	6.80	-	11.52	0.056	0.020	0.015	0.077	83

(cont'd)

(Table 16 - concluded)

Heat No and Position	Sample Location*	Chemical Analyses, %							H_2, ppm
		Al	Sn	Zr	Fe	C	N_2	O_2	
(Ti-7Al-12Zr)									
V-1787 Mid.	A	6.71	-	11.50					
	B	6.80	-	11.48					
	C	6.78	-	11.49					
	D	6.78	-	11.47					
	Av.	6.77	-	11.49	0.058	0.018	0.012	0.075	119
V-1787 Bot.	A	6.79	-	11.70					
	B	6.85	-	11.67					
	C	6.77	-	11.70					
	D	6.84	-	11.77					
	Av.	6.81	-	11.71	0.051	0.024	0.016	0.076	74
V-1788 Top	A	6.83	-	11.67					
	B	6.82	-	11.74					
	C	6.77	-	11.74					
	D	6.76	-	11.67					
	Av.	6.80	-	11.71	0.052	0.016	0.017	0.080	53
V-1788 Mid.	A	6.82	-	11.86					
	B	6.88	-	11.89					
	C	6.82	-	11.77					
	D	6.77	-	11.84					
	Av.	6.82	-	11.84	0.052	0.014	0.013	0.089	86
V-1788 Bot.	A	6.82	-	11.82					
	B	6.87	-	11.79					
	C	6.85	-	11.77					
	D	6.77	-	11.77					
	Av.	6.83	-	11.79	0.048	0.016	0.018	0.082	106

(*) Sampling of Slab Slices -



Note: Samples for oxygen and hydrogen were taken adjacent to Location D.

variability of the six ingots in Table 16 is at a very acceptable level, and since no changes in melting procedure were made between the two sets of ingots, it is concluded that the zirconium content of V-1540 and V-1541 was considerably more uniform than had been reported [5]. These same comments and conclusions also apply to the zirconium analyses listed for the Ti-7Al-12Zr sheets in Table 7 of the Ninth Bimonthly Report[3].

Following chemical analyses, sheet bars were scheduled and cut, rolled to an intermediate stage from 1880-1900F, conditioned, vacuum annealed at 1350F, and several sheets were finish pack rolled from 1750F. However, two areas of difficulty were encountered. First, during initial rolling from 1880-1900F, many of the sheet bars developed rather severe edge and surface cracks. The source of this difficulty, which had never been observed previously on these two alloys, was traced to incomplete conditioning of the pressed slabs. Once this was discovered, the remaining bars were more thoroughly conditioned and then rolled to the intermediate stage with no more difficulties. However, as a result of the additional conditioning required, both of the intermediate rolled bars as well as the original sheet bars, the weight of the bars was significantly lower than originally planned. Therefore, the length or gage of many of the finished sheets will be less than ordered.

The second problem encountered was that of transverse ripples obtained during finish pack rolling from 1750F. Some of these defects were sufficiently severe to require that several sheets be scrapped. Adjustments in rolling techniques and pack thickness have been implemented to minimize this difficulty, but, even so, a shortage of slab stock was foreseen as a result of these lost sheets. Therefore, one additional 1700-pound ingot of each composition is being melted and will be ready for processing early in the next period. Thus, a total of four 1700-pound heats of each alloy will be available to supply 2000 pounds of finished sheet from each grade in the contract.

A general status of the production of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr sheets is tabulated as follows:

Status of Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr Sheets*

Gage, in	No. of Sheets Ordered	No. of Sheets Applied	No. of Sheets Scrapped	No. of Sheets Completed
Ti-5Al-5Sn-5Zr				
0.020	18	27	4	0
0.040	14	18	-	0
0.062	12	10	-	0
0.090	10	11	-	0
0.125	8	8	-	0
Total	62	74	4	0
Ti-7Al-12Zr				
0.020	18	21	9	0
0.040	14	18	3	0
0.062	12	12	-	0
0.090	10	10	-	0
0.125	8	8	-	0
Total	62	69	12	0

(*) Does not include material from one additional 1700-pound ingot of each alloy currently being melted.

FUTURE WORK

Ti-8Al-1Mo-1V

Item 1

During the next period, the laboratory study will be completed on determining the effect of hydrogen on the tensile and creep-stability

properties of Ti-8Al-1Mo-1V sheet. Several sheets from M-9519 will be duplex annealed and evaluated to determine if any unusual processing difficulties are encountered in this annealing cycle. Property uniformity and additional welding studies will be performed on a typical mill annealed 0.062in sheet of Ti-8Al-1Mo-1V.

Item 2

Processing, testing, and inspection of the 92 sheets from the five ingots will be continued with much of this material scheduled for completion during the next period. A tentative automatic release of property specification will be proposed and, wherever possible, sheets will be shipped to Navy-approved customers. Processing of the last 1700-pound ingot of Ti-8Al-1Mo-1V will be continued with intermediate and finish rolling scheduled for the next period.

Ti-5Al-5Sn-5Zr and Ti-7Al-12Zr

Item 1

Several laboratory investigations will be completed by the end of the next report period including contamination studies, results of additional property evaluation, and the hydrogen study for both alloys. The additional welding investigation will also be continued. Testing and inspection of the 26 sheets from the first two ingots will be completed which will dictate whether any processing changes are required for the balance of the sheets in the contract. One 0.062in sheet of each alloy will also be sectioned for property uniformity studies.

Item 2

The balance of intermediate rolled sheet bars from the first six 1700-pound ingots will be finish rolled and processing continued toward finished sheet product. Processing of two additional 1700-pound heats, one of each alloy, will be initiated; this will include pressing, chemical analyses, and intermediate rolling of sheet bars. Efforts will also be made to establish an automatic release property specification for each alloy and to ship, wherever possible, finished sheets to Navy-designated customers.

— — —

ab

REFERENCES

1) Eighth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Aeronautics' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 30 June 1961

2) Fifth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Navy Bureau of Aeronautics' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 17 October 1960.

3) Ninth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Aeronautics' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 7 July 1961.

4) Tenth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Aeronautics' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 31 July 1961.

5) Sixth Bimonthly Report, Titanium Sheet Rolling Program for Ti-8Al-1Mo-1V, Ti-5Al-5Sn-5Zr, and Ti-7Al-12Zr, Navy Bureau of Aeronautics' Contract NOas 59-6227-c, Titanium Metals Corporation of America, 30 March 1961.

\- - -

DISTRIBUTION LIST

(Contract NOas 59-6227-c)

Chief, Bureau of Aeronautics
Department of the Navy
Washington 25, D. C.

Mr. R. F. Malone
Crucible Steel Corporation
Midland, Pennsylvania

Mr. S. R. Seagle
Reactive Metals, Inc.
Niles, Ohio

Mr. William J. Youden
Consultant
National Bureau of Standards
Washington 25, D. C.

Mr. Robert Wichser
Republic Aviation Corporation
Farmingdale, Long Island, N.Y.

Mr. L. P. Spalding
North American Aviation, Inc.
International Airport
Los Angeles 45, California

Mr. W. H. Sharp, Metallurgist
Pratt and Whitney Aircraft Corp
East Hartford 8, Connecticut

Mr. L. L. Gould
Staff Metallurgist
Materials Advisory Board
National Research Council
2101 Constitution Avenue, N.W.
Washington 25, D. C.

Mr. H. R. Ogden
Defense Metals Information Center
Battelle Memorial Institute
505 King Avenue
Columbus, Ohio

Mr. Howard Middendorp
Wright Air Development Center
Wright-Patterson Air Force Base,
Ohio

Mr. S. V. Arnold
Physical Metallurgy Division
Watertown Arsenal Laboratory
Watertown, Massachusetts

Mr. J. Sessler
Metallurgical Research Laboratories
Syracuse University Research Inst.
Syracuse, New York

Mr. T. H. Gray
Assistant Chief Metallurgist
Boeing Aircraft Corporation
Seattle, Washington

Dr. George Gerard
Professor of Aeronautical Engineering
New York University
New York 53, New York

Commander, Headquarters
Air Materiel Command
Wright-Patterson Air Force Base,
Ohio
Attn: MCPBM, Mr. Robert Jamison

Dr. D. J. McPherson, Manager
Metallurgical Research Department
Armour Research Foundation
10 West 36th Street
Chicago 16, Illinois

Defense Metals Information Center
Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio

(Contract NOas 59-6227-c)

Dr. W. J. Harris, Jr.
National Academy of Sciences
2101 Constitution Avenue, N.W.
Washington 25, D. C.

Department of the Navy
Inspector of Naval Material
1783 East 11th Street
Cleveland 14, Ohio

Mr. A. Hurlich
Engineering Materials Group
Mail Zone 595-2-41a
Convair-Astronautics
Division of Generay Dynamics Corp
San Diego 12, California

Mr. S. R. Carpenter
Producibility Supervisor
Mail Zone 6-148
Convair, Division of General
Dynamics Corporation
San Diego 12, California

Grumman Aircraft Engineering Corp
Bethpage, Long Island, New York
Attn: Mr. F. X. Drumm

North American Aviation, Inc
Columbus, Ohio
Attn: Mr. Paul Maynard

Chance-Vough Aircraft Corp
Dallas, Texas
Attn: Mr. John Seeger

Republic Steel Corporation
Massillon, Ohio
Attn: Mr. H. O. Mattes

Lockheed Aircraft Corporation
Structural Research Laboratory
Marietta, Georgia
Attn: Mr. P. J. Hughes

Battelle Memorial Institute
505 King Avenue
Columbus 1, Ohio
Attn: Dr. R. I. Jaffee

Headquarters, Wright Air Development Center
Wright-Patterson Air Force Base, Ohio
Attn: Mr. Edward Dugger
Material Laboratory

Mr. John H. Garrett
Chief, Materials Division
Office, Director of Research
and Engineering
The Pentagon
Washington 25, D. C.

Commanding Officer
Diamond Ordnance Fuze Laboratory
Attn: Tech Ref Sec ORDTL 012
Washington, D. C.

Commanding Officer
Naval Air Material Center
Aeronautical Materials Laboratory
Philadelphia 12, Pennsylvania

Bureau of Ordnance (Re-c)
Washington 25, D. C.

Bureau of Ships
(Code 343)
Washington 25, D. C.

Naval Research Laboratory
Washington 25, D. C.

Office of Naval Research
Code 423
Washington 25, D. C.

(Contract NOas 59-6227-c)

National Aeronautics and Space Administration
1520 H Street, N. W.
Washington 25, D. C.

Aerospace Industries Association
7660 Beverly Boulevard
Los Angeles 36, California
Attn: Mr. H. D. Moran (10 copies)

Executive Office of the President
Office of Defense Mobilization
Attn: Mr. J. H. Stehman
Washington 25, D. C.

Department of Commerce
Business Defense Supply Agency
Washington 25, D. C.
Attn: Mr. H. Cullen

General Electric Company
Jet Engine Department
Cincinnati 15, Ohio
Attn: Mr. E. W. Ross
Building 501

B. F. Goodrich Aviation Products
Wheel and Brake Plant
Troy, Ohio
Attn: Mr. G. F. Meeker

TITANIUM METALS CORPORATION OF AMERICA

first in titanium—
GENERAL OFFICE—233 BROADWAY
NEW YORK 7, NEW YORK

Titanium Sponge
Titanium Powder
Commercially-Pure and Titanium-Base Alloys
Sheet
Foil
Strip
Plate
Bar
Rod
Wire
Seamless Tubing
Forging Billets
Extruded Shapes
Rolled Shapes

SALES OFFICES

NEW YORK 7, N. Y.
233 Broadway
BArclay 7-0494

CLEVELAND 13, OHIO
Illuminating Building
MAin 1-5450

CHICAGO 2, ILLINOIS
6 North Michigan Avenue
STate 2-5947

DALLAS 35, TEXAS
Exchange Bank Building
FLeetwood 7-4353

LOS ANGELES 22, CALIFORNIA
6465 Corvette Street
RAymond 3-8567

UNCLASSIFIED

UNCLASSIFIED